Effects of Dynamic Landscape Processes on the Spatiotemporal Distribution and Quality of Chinook Salmon Spawning Habitat in Mountain Watersheds

FINAL REPORT

EFFECTS OF DYNAMIC LANDSCAPE PROCESSES ON THE SPATIOTEMPORAL DISTRIBUTION AND QUALITY OF CHINOOK SALMON SPAWNING HABITAT IN MOUNTAIN WATERSHEDS

Joint venture agreement between the:
US Forest Service, Rocky Mountain Research Station
Agreement Number: RJVA #03-JV-11222014-060

and

University of Idaho
Project Number: FKK846

Prepared by:

Mikolaj Lewicki and Klaus Jorde
University of Idaho
Center for Ecohydraulics Research
Department of Civil Engineering
Idaho Water Center, 322 E. Front St.
Boise, ID 83702

John M. Buffington and Russell F. Thurow
US Forest Service, Rocky Mountain Research Station
Idaho Water Center, 322 E. Front St.
Boise, ID 83702

with contributions from:

Yantao Cui, Hydraulic Engineer
1126 Crowe Place, Concord, CA 94518

and

Daniel J. Isaak and Dave Nagel
US Forest Service, Rocky Mountain Research Station
Idaho Water Center, 322 E. Front St.
Boise, ID 83702

Reporting Period: January 1, 2004 – October 31, 2007

TABLE OF CONTENTS

1 PURPOSE

The purpose of this agreement is to develop a better understanding of the geomorphic controls on the spatial distribution and quality of Chinook salmon spawning habitat in mountain catchments, and to predict how spawning habitat changes over space and time in response to basin disturbances (e.g., fire, debris flows, flooding).

The following report describes progress toward achieving objectives stated in the project workplan. A list of project publications and presentations is provided in section 5.

2 STUDY AREA

This study continues and builds upon previous work by the collaborators conducted in the Middle Fork Salmon River (MFSR) basin (Fig. 1). As such, we capitalize on an extensive data set of channel characteristics, redd surveys, and GIS layers developed in those studies (Thurow 2000; Isaak et al. 2005). The MFSR was initially selected as the study area for several reasons:

- Remaining Chinook salmon stocks are wild and indigenous, unaltered by hatchery supplementation. Consequently, the ability of the salmon population to respond to the quality and quantity of the available habitat has not been altered. Wild, indigenous, Chinook salmon populations like those in the MFSR are rare; Thurow et al. (2000) reported their presence in 4% of the potential historical range and 15% of the current range in the Columbia River basin and portions of the Klamath River basin.
- Much of the MFSR basin is located within the Frank Church River of No Return Wilderness. As such, most of the drainage has had little disturbance from anthropogenic activities, so habitat quality has not been substantially altered in most areas. Widespread degradation of habitat would be expected to confound a spatial analysis of freshwater habitat by influencing fish distribution and abundance.
- The large drainage area of the basin (> 7,000 km^2) provides an opportunity for a large sample size. About 650 km of tributaries and 170 km of the mainstem are accessible to Chinook salmon (Thurow 1985). This increases the likelihood of a sample size large enough to complete a robust spatial analysis.

In addition to the MFSR, study sites in the Middle Fork Boise River (MFBR) will be used (Fig. 1). Recent post-fire debris flows in this drainage offer an opportunity to test and calibrate our dynamic sediment routing model. Although historical Chinook salmon populations have been extirpated from the MFBR, the physiography and geomorphic processes are comparable to the MFSR, allowing extension of results to that basin.

3 GEOMORPHIC MODELS

Three approaches will be used for modeling geomorphic controls on spawning habitat: 1) correlation of the observed location and quality of spawning sites with landscape features (geology, channel gradient and confinement, land use, etc.); 2)

mechanistic prediction of the abundance and spatial distribution of spawning gravels as a function of channel type and associated hydraulics (Buffington et al. 2004); and 3) development of a dynamic model for routing sediment through the river network as a function of basin hydrology and stochastic sediment inputs (floods, debris flows), allowing investigation of the spatial and temporal changes in spawning habitat availability. Each of these approaches is described in the project workplan, with a summary of progress to date listed below.

3.1 Landscape features model: Black box approach

- 2004– The bulk of this work was deferred until 2005 due to difficulties in hiring a postdoctoral researcher for the project. Nevertheless, some initial data were compiled. Basin topography, stream gradient, and drainage area were obtained from a digital elevation model. GIS was used to overlay basin geology on these data. Remaining tasks include using GIS and aerial photography to overlay more detailed geologic maps, identify locations and extent of historic anthropogenic disturbance (mining, grazing, roads), and identify locations and extent of historic natural disturbance (fire, landslides, flood events). Some preliminary results of relating observed locations of Chinook salmon spawning to broad-scale geomorphic features in the MFSR indicate that spawning sites are correlated with channel slope (in particular, the control of channel slope on the occurrence of pool-riffle morphologies) (Fig. 2), stream width (as influenced by drainage area and discharge) (Fig. 3), and valley confinement (as controlled by glaciation and geomorphic history). We found that the highest densities of spawning sites occurred in broad alluvial valleys (Fig. 4). These areas are typically low-gradient pool-riffle reaches that commonly contain suitable spawning substrates. However, median grain sizes tend to be on the low end of what is considered suitable (typically 10-20 mm). Marginal substrate size may be offset by favorable hyporheic flow through these alluvial valleys (e.g., Baxter and Hauer, 2000). Alternatively, extensive side-channels may increase offspring success, resulting in relatively larger densities of returning fish.
- 2005–This portion of the project has been deferred indefinitely because it has become apparent that most of the postdoctoral researcher's time will be spent implementing the sediment routing model (section 3.3).
- 2006-2007–This task has been deferred (see above).

3.2 Hydraulic model

- 2004
  - *Subreach grain size*–Field measurements were conducted in 2004 to quantify the occurrence of textural patches and their grain-size characteristics in channel types used by spawning salmonids (pool-riffle, plane-bed, and step-pool channels). Forty three channels were sampled throughout the MFSR basin in locations where reach-average characteristics had been obtained in previous studies by the collaborators (Isaak et al. 2005). These data will be used to refine predictions of spawning gravel availability by correcting reach-average grain-size predictions for subreach variability of sediment size as a function of channel type.

- *Barriers and channel size*–Initial examination of presence/absence data suggested that MFSR Chinook salmon do not spawn in channels with bankfull widths less than about 8 m, indicating a critical drainage area of about 50 km^2 (Fig. 3). This suggests that much of the drainage network in mountain basins, which is typically comprised of low-order channels of small drainage area (Buffington et al. 2004), will not support Chinook salmon.

- 2005
  - *Network extent*–Initial exploration of this task revealed substantial analytical problems to resolve. To expand our grain-size predicts across the entire MFSR channel network it is necessary to determine channel slope for each segment of the network. Our prior approach for determining channel slope involved digitizing contour crossing of the stream network as observed on 1:24,000 topographic maps and overlaying this information on basin digital elevation models (DEMs). However, this was not a feasible approach for the entire stream network of the MFSR, which comprises over 10,000 km of channel, most of which are steep segments with frequent contour crossings. Alternative, automated approaches for determining channel slope would likely cause slope errors that will cascade directly into the predictions of grain size and spawning habitat availability. One alternative was to generate a synthetic channel network based on values of critical drainage area (Montgomery and Foufoula-Georgiou, 1993; Tarboton 2000). However, this approach does not preserve channel pattern in low-gradient areas (straight reaches are predicted where meandering channels would normally be observed), causing incorrect representation of channel length and thus slope. Another alternative was to overlay the hydrocoverage on the DEM (preserving true channel pattern and true channel lengths), with slope calculated at fixed intervals along the stream length. However, this approach can distort channel slopes if the specified reach length averages multiple contour crossings. Furthermore, topographic distortion during DEM construction, as well as georeferencing errors of the hydrocoverage, can cause the hydrocoverage to be erroneously placed on footslopes and mislocated in general, resulting in elevation errors and consequent slope errors. We further examined these issues to determine if an acceptable automated approach can be developed that minimizes slope errors.

- 2006-2007
  - *Network extent*–Our continued investigation of how to correctly determine channel slope from DEMs was summarized in a presentation by Nagel et al. (2006; Appendix B). Based on these findings, we used a hybrid approach that selects one of three methods for determining channel slope, depending on general slope classes (mainstem (low slope), mid slope, and high slope) (Nagel et al. 2006). We also intend to explore use of other recent techniques, such as "drainage-enforced DEMs" (Davies et al. 2007).
  - *Geology*–We incorporated primary differences in geology (batholith vs. volcanics) in our bankfull depth predictions (Fig. 11 of Isaak et al. 2005) and determined that more detailed geologic classification (finer-scale lithologic

differentiation) of stream reaches does not improve model predictions of bankfull depth.

- *Roughness correction*–We developed an alternative prediction of bankfull Shields stress that allows differentiation of channel type and associated roughness, improving predictions of grain size and potential salmonid spawning habitat. Bankfull Shields stress (τ^*) is now predicted as a power function of channel slope (S), bankfull depth (h) and bankfull width (W) ($\tau^* = k(Sh/W)^n$). This is similar to our previous prediction as a function of bankfull shear stress (ρghS), but now includes channel width as a discriminating factor. Geology was identified as a control on bankfull channel characteristics (see above), and we intend to apply autoregressive analyses to empirically determine other potential controls that would allow further improvement of grain-size and predictions and potential spawning habitat availability.
- *Products*–We are drafting two manuscripts from the above analyses, one focused on methods for determining channel slope (Nagel et al. 2006; in prep.), and one that compares observed locations of Chinook salmon spawning to those predicted from our hydraulic model (Buffington et al. in prep.).

3.3 Sediment routing model

3.3.1 Model development

- 2004–Dr. Yantao Cui was subcontracted to develop the basic numerical code for a network sediment routing model that also accounts for channel response to sediment pulses. A beta version of the model was completed.
- 2005–The software and supporting documentation for the model were delivered (Cui 2005; Appendix A).

3.3.2 Model testing and calibration

- 2004–We learned to use the beta version of the sediment routing model and began testing it at the MFBR field site. To provide a longer term data base for evaluating the model, field crews conducted repeat surveys of the MFBR debris-flow deposits (Fig. 5), providing a second year of data. Topographic surveys and pebble counts of the debris fans and mainstem channel were conducted over a 7 km reach (Fig. 6). These data will be used to document channel evolution of the mainstem MFBR following the 2003-2004 debris-flow events and to test and calibrate the sediment routing model.
- 2005–Field crews conducted repeat surveys of the MFBR debris-flow deposits, adding a third year to our data base. Additional cross sections and pebble counts were added to fill in missing information and extend the model domain both upstream and downstream.
- 2006-2007–A draft manuscript was prepared comparing predicted versus observed channel response to post-fire debris flows at the MFBR test site

(Appendix C). The model performed well, providing reasonable predictions of debris-fan evolution, changes in streambed elevation, and sediment size over time. Predictions indicate that the sediment wave introduced by the debris flows will move rapidly through this steep, confined river, with the channel profile recovering within about 10 years. In contrast, the model indicates that it will take about 25 years for median grain sizes to recover to pre-disturbance conditions. Repeat surveys of the study site were also conducted in 2007, and these data will be used to further evaluate the model before manuscript submission.

3.3.3 *Predicting aquatic impacts*

- 2004–No work was completed under this task in 2004.
- 2005–Cape Horn Creek, a sub-basin of the MFSR that is a core spawning area for Chinook salmon (Isaak et al. 2003), was selected as a study area for this task. Using Cui's (2005) model, we examine spawning habitat response to a simulated sediment pulse from a hillside landslide in a confined section of the river. Field work was conducted at the site to obtain necessary data for implementing the simulation (topographic surveys, and grain-size sampling).
- 2006-2007–A draft manuscript has been prepared that reports the findings of our simulations. Downstream impacts to spawning gravel quality were assessed in terms of spatial and temporal changes in both the median grain size (Kondolf and Wolman 1993) and the percentage of fine material (Bjornn and Rieser 1991) as the landslide pulse is routed through the channel. Sensitivity to the size distribution of the landslide material is also explored. Potential effects of sediment pulses on salmonid habitat are also examined at the MFBR test sites (Appendix C).

3.3.4 *Stochastic disturbance and network routing model*

- 2004–Field work was conducted to measure characteristics of recent, post-fire, debris-flow deposits (volume and grain size of debris fans) in both the MFSR (Pistol Ck drainage) and the MFBR (Bear, Lake, and Steel creeks, section 3.3.2). These data will be used to predict post-fire debris-flow characteristics in our stochastic disturbance model.
- 2005– The Loon/Mayfield drainage, a sub-basin within the MFSR watershed, was selected as a test site for implementing the stochastic disturbance and network routing model. Cui's (2005) numerical model was tailored to this sub-basin and initial testing of model stability and behavior was conducted under controlled conditions (2- and 100-year floods without debris-flow inputs). We used the Wilcock and Crowe (2003) bedload transport equation in this analysis, and calibrated it to available bedload transport data from Idaho rivers (King et al. 2004). Field work was conducted in the Loon/Mayfield basin to obtain necessary data for implementing the network routing model (topographic surveys, and grain-size sampling).
- 2006-2007–Further work on implementing the stochastic disturbance and network routing model in the Loon/Mayfield drainage was completed. The model was

successfully stabilized and necessary input parameters were developed (hydrographs, probability of fire occurrence, probability of debris-flow occurrence, and debris-flow characteristics were estimated for each site throughout the entire watershed). The model is ready for implementation.

4 REFERENCES

Baxter, C.V., and R.F. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences **57**:1470-1481.

Bjornn, T.C., and D.W. Reiser. 1991. Habitat requirements of salmonids in streams. American Fisheries Society Special Publication **19**: 83-138.

Buffington, J.M., D.R. Montgomery, and H.M. Greenberg. 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Canadian Journal of Fisheries and Aquatic Sciences **61**:2085-2096.

Cui, Y. 2005. A bedload transport model for gravel-bedded river networks, unpublished report and software, 16 pp.

Davies, J.R., K.M. Lagueux, B. Sanderson, and T.J. Beechie. 2007. Modeling stream channel characteristics from drainage-enforced DEMs in Puget Sound, Washington, USA. Journal of the American Water Resources Association **43**:414-426.

Isaak, D.J., Thurow, R.F., Rieman, B.E., and J.B. Dunham. 2003. Temporal variation in synchrony among chinook salmon (Oncorhynchus tshawytscha) redd counts from a wilderness area in central Idaho. Canadian Journal of Fisheries and Aquatic Sciences **60**: 840-848.

Isaak, D.J., K. Jorde, J.M. Buffington, and R.F. Thurow. 2005. Spatial structure and dynamics of salmonid populations and their habitats. Joint venture agreement 01-JV-11222014-101. University of Idaho and USDA Forest Service Rocky Mountain Research Station. Final Report. 39 pp.

King, J.G., W.W. Emmett, P.J. Whiting, R.P. Kenworthy, and J.J. Barry. 2004. Sediment transport data and related information for selected gravel-bed streams and rivers in Idaho. U.S. Forest Service General Technical Report. Rocky Mountain Research Station. RMRS-GTR-131. 26 pp.

Kondolf, G.M., and M.G. Wolman. 1993. The sizes of salmonid spawning gravels. Water Resources Research **29**: 2275-2285.

Montgomery, D.R., and E. Foufoula-Georgiou. 1993. Channel network source representation using digital elevation models. Water Resources Research **29**: 3925-3934.

Nagel, D., J.M. Buffington, and D.J. Isaak. 2006. Comparison of methods for estimating stream channel gradient using GIS. 21st Annual ESRI Northwest GIS Users' Conference and Training, Spokane, WA, September 13-15.

Tarboton DG. 2000. TARDEM, a suite of programs for the analysis of digital elevation data. Utah State University: www.engineering.usu.edu/cee/faculty/dtarb/tardem.html.

Thurow, R.F. 1985. Middle Fork Salmon River fisheries investigations. Job completion report. Federal Aid in Fish Restoration Project F-73-R-6. Idaho Department of Fish and Game, Boise, ID.

Thurow, R.F. 2000. Dynamics of chinook salmon populations within Idaho's Frank Church Wilderness: Implications for persistence. *In* Wilderness Science in a Time of Change, Proceedings RMRS-P-15-VOL-3. *Edited by* S.F. McCool, D.N. Cole, W.T. Borrie, and J. O'Loughlin, USDA Forest Service Rocky Mountain Research Station. Ogden, UT. pp. 143-151.

Thurow, R.F, D.C. Lee, and B.E. Rieman. 2000. Status and distribution of Chinook salmon and steelhead in the interior Columbia River basin and portions of the Klamath River basin. *In* Sustainable fisheries management: Pacific salmon. *Edited by* E. Knudsen, C. Steward, D. MacDonald, J. Williams, and D. Reiser. CRC Press, Boca Raton, FA. pp. 133–160.

Wilcock, P.R., and J.C. Crowe. 2003. Surface-based transport model for mixed-size sediment. Journal of Hydraulic Engineering. **129**: 120-128.

5 PROJECT ACCOMPLISHMENTS

Publications in preparation

Buffington, J.M., D.J. Isaak, R.F. Thurow, and D. Nagel. in prep. Geomorphic controls on basin-scale availability of Chinook salmon spawning habitat in the Middle Fork Salmon River. *Can. J. Fish. Aquat. Sci.*

Lewicki M., J.M. Buffington, R.F. Thurow, and Y. Cui. in prep. Numerical model of channel response to post-fire debris flows in the Middle Fork Boise River, central Idaho. for submission to *J. Geophys. Res. Earth Surf.*.

Lewicki M., J.M. Buffington, R.F. Thurow, D.J. Isaak, and Y. Cui. in prep. Effects of sediment pulses on Chinook salmon spawning habitat in Cape Horn Creek, central Idaho. for submission to *Trans. Amer. Fish. Soc.*

Lewicki M., J.M. Buffington, R.F. Thurow, D.J. Isaak, and Y. Cui. in prep. Effects of post-fire debris flows on the spatiotemporal distribution of Chinook salmon spawning habitat in the Middle Fork Salmon River, Idaho: A network perspective. for submission to *Can. J. Fish. Aquat. Sci.*

Subcontract reports

Cui, Y. 2005. A bedload transport model for gravel-bedded river networks, unpublished report and software, 16 pp.

Presentations to scientific organizations (published abstracts & proceedings)

Nagel, D., J.M. Buffington, and D.J. Isaak. 2006. Comparison of methods for estimating stream channel gradient using GIS. *21st Annual ESRI Northwest GIS Users' Conference and Training*, Spokane, WA, September 13-15.

Lewicki, M., J.M. Buffington, R.F. Thurow, and D.J. Isaak. 2006. Numerical model of channel and aquatic habitat response to sediment pulses in mountain rivers of central Idaho. *EOS, Trans. Amer. Geophys. Union*, 87(52):Fall Meeting Supplement, Abstract H51B-0481.

Lewicki M. 2006. A numerical model of river channel response after disturbance caused by sediment pulses. *Posiedzenia Naukowe* PGI No.78 p.93-94

Invited lectures & workshops

Buffington, J.M., M. Lewicki, N.E. Scheidt, C.W. Welcker, B.E. Rieman, C.H. Luce, J.B. Dunham, and R.F. Thurow, Effects of fire on channel morphology and aquatic habitat in mountain rivers, Department of Geosciences Seminar Series, Warner College of Natural Resources, Colorado State University, Fort Collins, CO, September 10, 2007.

Buffington, J.M., D.J. Isaak, C.H. Luce, J.B. Dunham, J.A. McKean, D. Nagel, B.E. Rieman, R.F. Thurow, and M. Lewicki. Physical tools for predicting habitat patch networks at basin scales: Potential applications for understanding salmonid persistence in a changing environment. *Workshop on Predicting Salmon Habitat in Alaska*, The Nature Conservancy and Alaska Dept. of Fish & Game, Anchorage, AK, May 17-19, 2006.

Buffington, J.M., D.R. Montgomery, H.M. Greenberg, D.J. Isaak, R.F. Thurow, and D. Nagel. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments: Examples from western

Washington and central Idaho. *Workshop on Predicting Salmon Habitat in Alaska*, The Nature Conservancy and Alaska Dept. of Fish & Game, Anchorage, AK, May 17-19, 2006.

Thurow, R. 2006. Overview of Chinook salmon research within the Big Creek and Middle Fork Salmon river drainages. Big Creek Symposium. University of Idaho, Moscow, April 14.

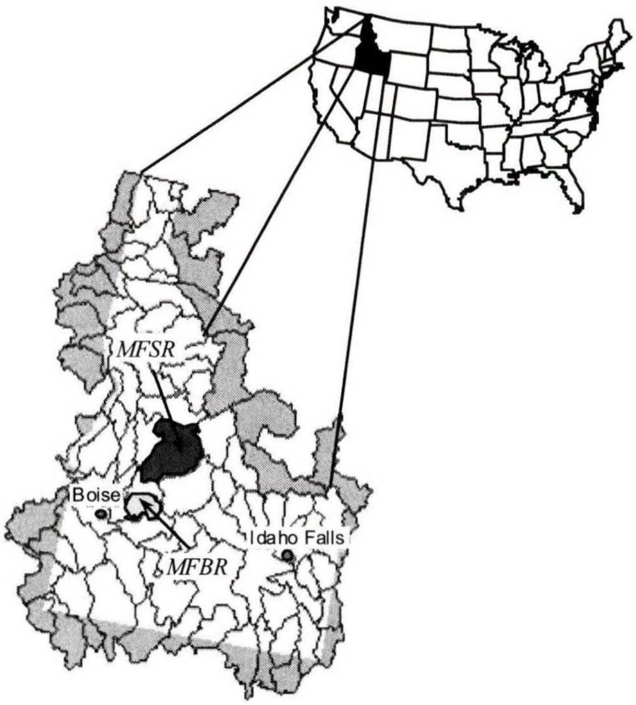


Fig. 1: Study areas in central Idaho: Middle Fork Salmon River (MFSR) and Middle Fork Boise River (MFBR).

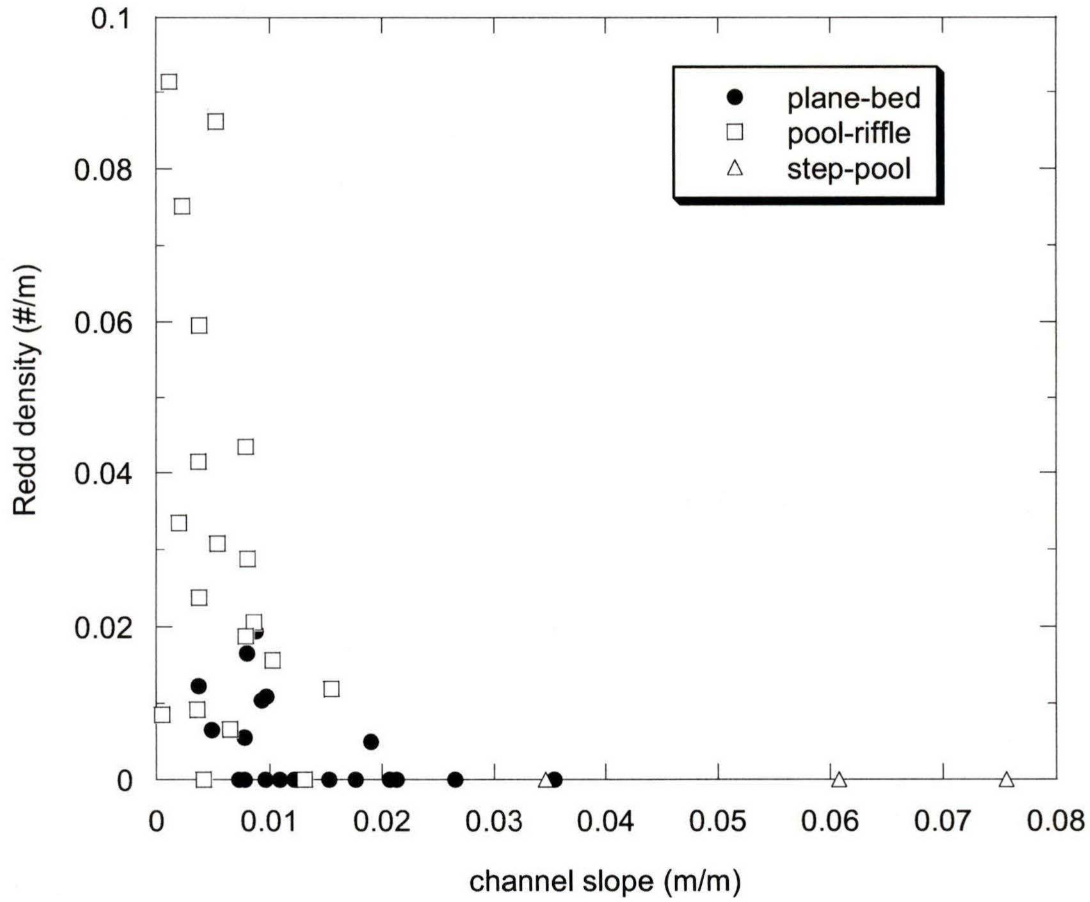


Fig. 2: Observed densities of Chinook salmon redds as a function of channel slope and channel type within the MFSR. Data are limited to sites within the historic range of Chinook salmon spawning within the basin (Isaak et al. 2005).

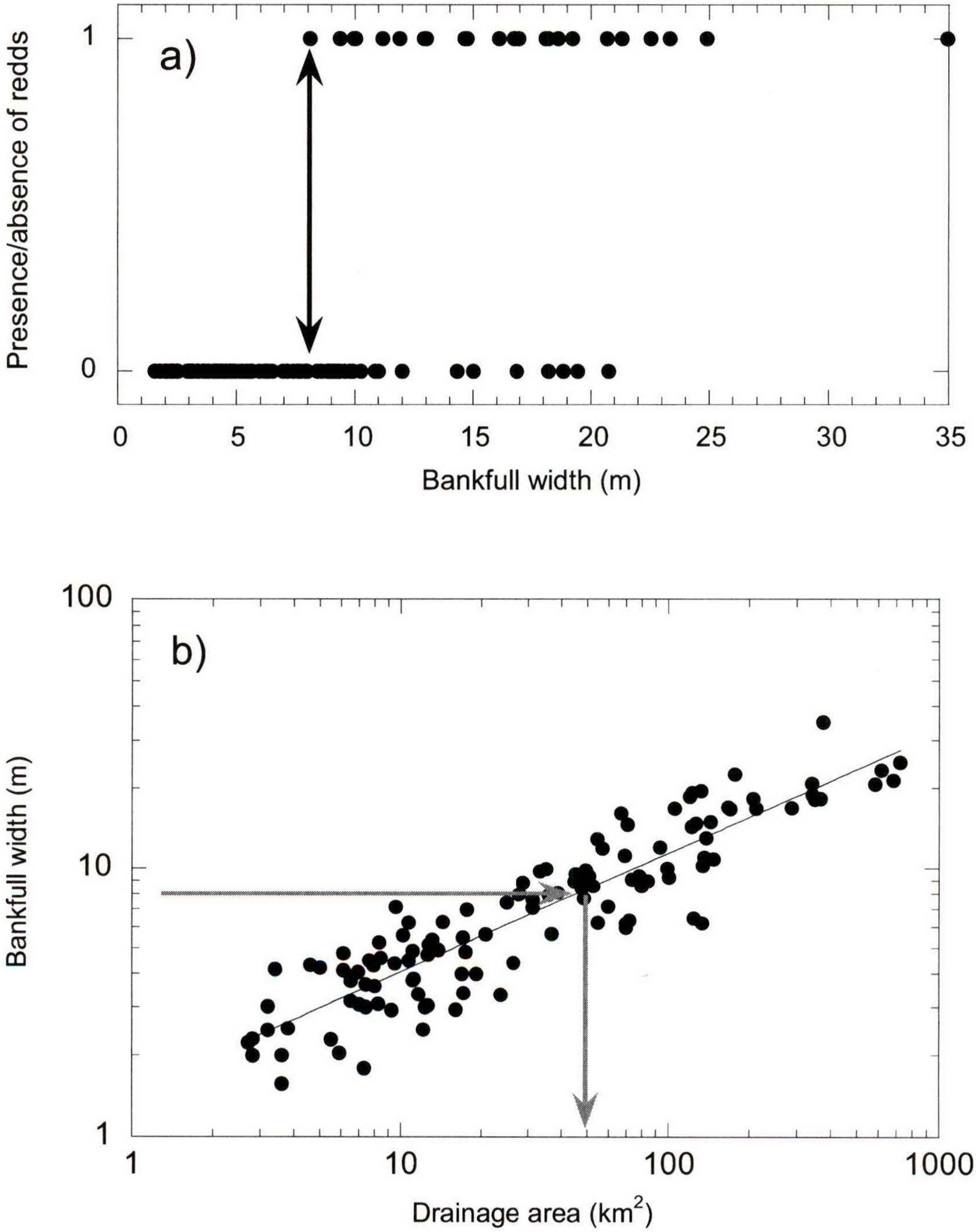


Fig. 3: Presence/absence of Chinook salmon redds in the MFSR as a function of a) bankfull channel width which is, in turn, a function of b) drainage area.

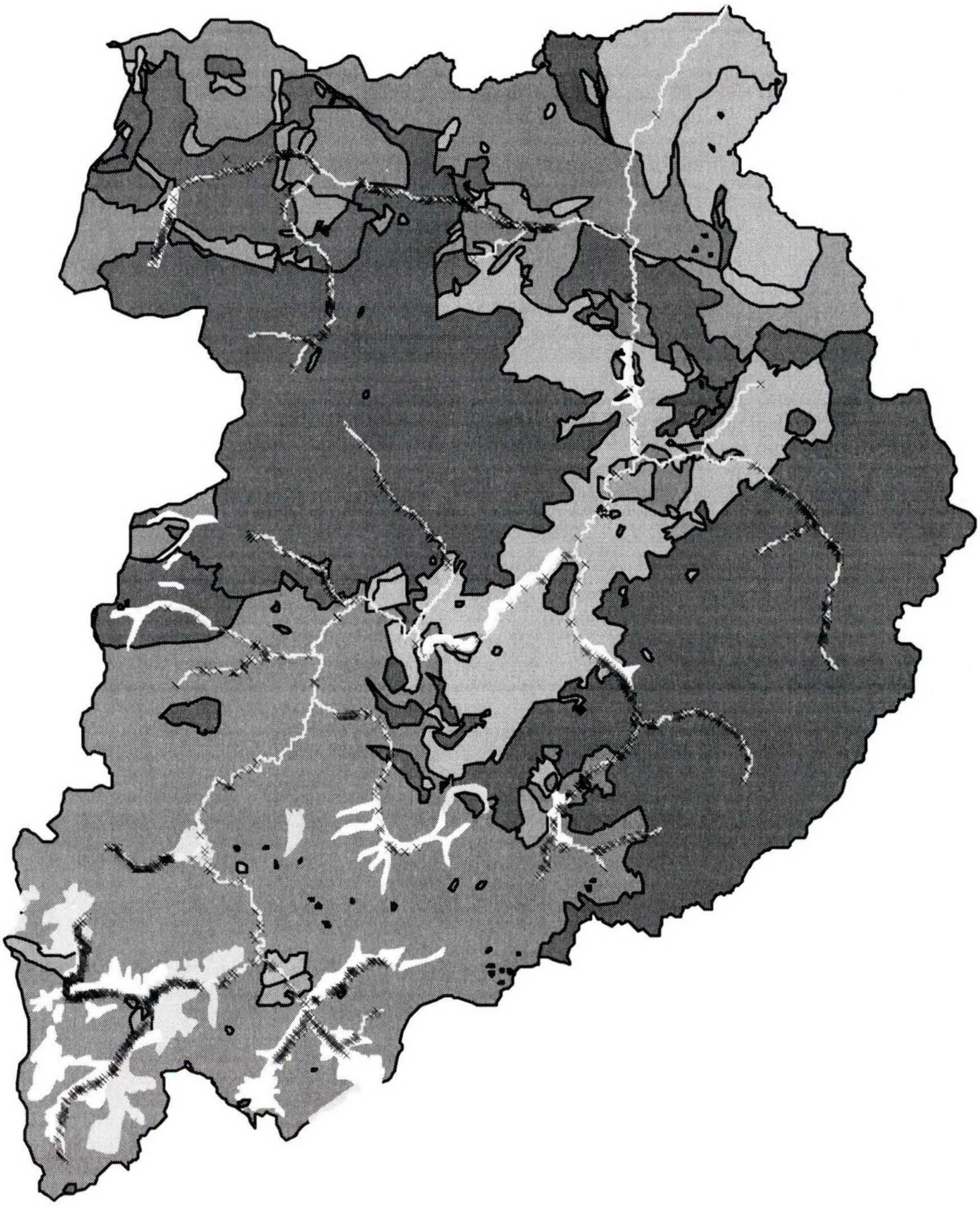


Figure 4: Channel network (cyan segments) and locations of Chinook salmon redds (x's) overlain on basin geology of the Middle Fork Salmon River. Yellow and green units are alluvium, typically occurring in unconfined valleys. From Buffington et al. (2003) and Isaak et al. (2005).

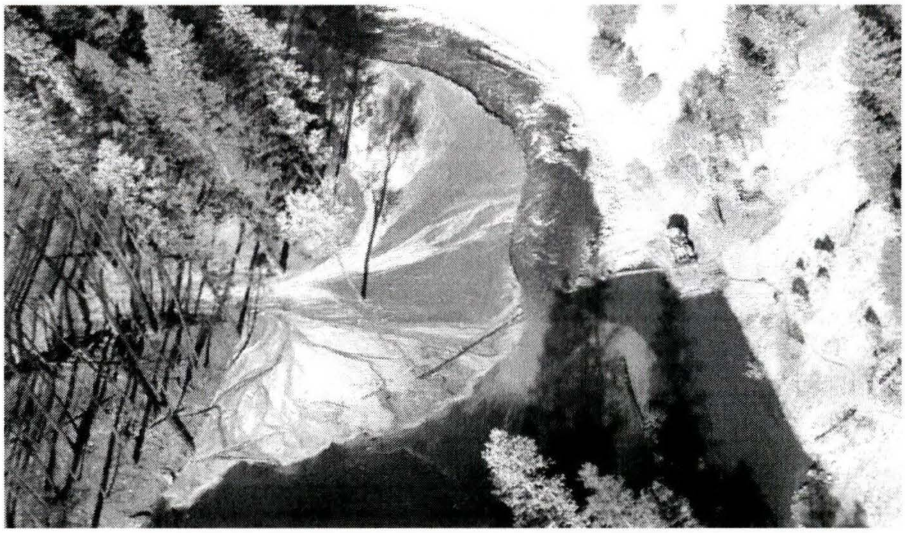


Fig. 5: Bear Creek debris-flow fan, Middle Fork Boise River (MFBR), 2003.

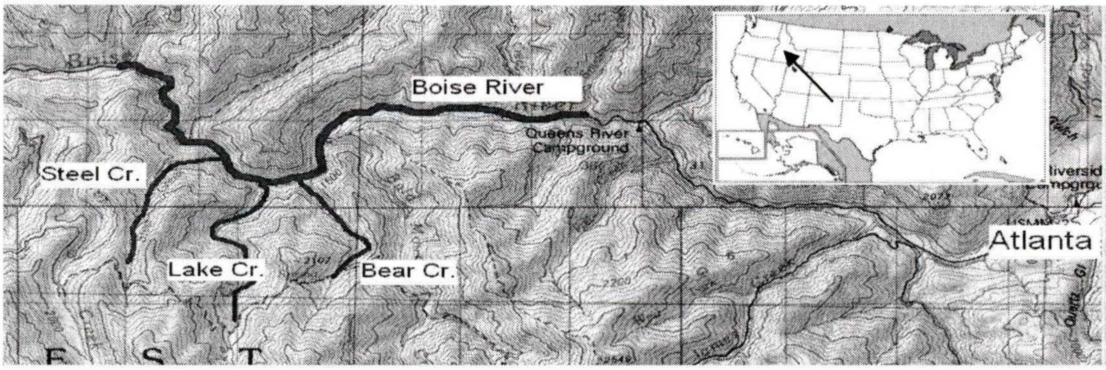


Fig. 6: Model domain for the Middle Fork Boise River test site, showing three point sources of sediment (tributary debris fans from Bear, Lake and Steel creeks) along a segment of the MFBR below the town of Atlanta.

YANTAO CUI, PH.D., HYDRAULIC ENGINEER
(Hydraulics, Hydrology, Sediment Transport, Fluvial Geomorphology, and Software Development)
1126 Crowe Place, Concord, CA 94518, 925-429-0465, 925-429-0585 (fax), www.cui.riverprofessionals.com

May 23, 2005

Dr. Klaus Jorde
Civil Engineering-Boise Center
800 Park Blvd., Suite 200
Boise, ID 83706

RE: Final Deliverable for Contract UI No. FKK846

Dear Dr. Jorde:

Enclose please find five (5) copies of a technical report entitled "A Bedload Transport Model for Gravel-bedded River Networks". This is the final deliverable, which concludes the contract between University of Idaho and Dr. Yantao Cui under the above contract number.

Please don't hesitate to contact me at the address and numbers list on this letter, or by e-mail at cui@riverprofessionals.com if you have questions. It has been a pleasure working on the project.

Yours truly,

Yantao Cui
Ph.D., Hydraulic Engineer

Encl: Five (5) copies of technical report
cc: Dr. John Buffington

A BEDLOAD TRANSPORT MODEL
FOR
GRAVEL-BEDDED RIVER NETWORKS

Prepared for

Department of Civil Engineering
University of Idaho
800 Park Blvd.,
Boise, ID 83712

Prepared by

Yantao Cui, Ph.D., Hydraulic Engineer
1126 Crowe Place
Concord, CA 94518

May 2005

TABLE OF CONTENTS

1. INTRODUCTION

This report documents the development of a bedload transport model applicable for gravel-bedded channel networks. The sole purpose of this report is to give readers necessary information with regard to the development of the computer program so that they can apply the model by modifying the input files. It is also hoped that readers with a working knowledge in FORTRAN computer language and a good understanding in sediment transport theories and practices will be able to make additional modifications to the computer program with the help of this report.

The program is written in FORTRAN 90 computer language and is debugged/compiled with DIGITAL Visual FORTRAN 6.0 under Windows environment. Compiling and running the program with a different FORTRAN compiler or under different environment may result in unexpected errors.

Input data for the model are stored in eight text files. Results are printed in a single text file. A user-friendly Excel/VBA program, *EFSalmon.xls*, is written to help users to extract output data into six Excel workbooks.

The computer program was named *EFSalmon* after the *Salmon River* in the State of Idaho, and *EF* can be interpreted as whatever you wish.

2. BRIEF DESCRIPTION OF TECHNICAL BACKGROUND

The theory and techniques used in *EFSalmon* are primarily from the sediment pulse work of Cui and Parker (2005) and Cui et al. (2003), in which heterogeneous coarse sediment particles (> 2 mm) are routed through single channels. The technique used for routing sediment and water through channel network is primarily based on the work of Cui and Parker (1999), and Cui et al. (2001). Only a brief description of governing equations is given in this section, while the details of the theories and techniques can be found in Cui et al. (2003) and Cui and Parker (2005).

EFSalmon is a decoupled model, in which parameters for flow (*i.e.*, depth, velocity, shear stress, *etc.*) and channel bed (*i.e.*, bed elevation, surface and subsurface grain size distribution, *etc.*) are updated at each time step with the application of quasi-steady flow assumption when calculating flow parameters. Further more, standard backwater calculation is applied for low Froude number flow conditions, and quasi-normal flow assumption is employed for high Froude number flow conditions. The basic equations for flow parameter calculation are:

$$\frac{dh}{dx} = \frac{S - S_f}{1 - F_r^2}, \quad F_r < F_{rn} \tag{1a}$$

$$S_f = S, \quad F_r \geq F_{rn} \tag{1b}$$

in which h denotes water depth; x denotes upstream distance; S denotes local channel bed slope; S_f denotes friction slope; F_r denotes local Froude number; and F_{rn} is Froude number with a value close to and less than unity. F_{rn} is set to 0.8 in the sample run presented in this report. It needs to be noted that distance x is taken as an unconventional upstream direction due to the special need of describing a channel network. Equation (1) is an approximation of the full St. Venant shallow water equations under quasi-steady assumptions, and certain details of the approximations of the equations can be found in Cui and Parker (2005).

Slope S is defined as

$$S = -\frac{\partial(\eta_b + \eta)}{\partial x} \tag{2}$$

in which η_b denotes a reference elevation; and η denotes the thickness of sediment deposit measured from the reference elevation. For shallow sediment deposit, the reference elevation, or base elevation, must be set at the bedrock elevation. For deep sediment deposit, the reference elevation can be set at a depth where the channel bed will not have a chance to scour to. Froude number Fr is approximated as

$$F_r = \left(\frac{Q_w^{\ 2}}{gB^2h^3}\right)^{1/2} \tag{3}$$

in which Q_w denotes local discharge; g denotes acceleration of gravity; and B denotes bankfull channel width. Note that the width to depth ratio of the channel is assumed to be high so that it can be approximated as a rectangular channel. Friction slope S_f is calculated with Keulegan-type resistance relation:

$$S_f = \frac{u_*^{\ 2}}{gh}, \quad \frac{Q_w}{Bhu_*} = 2.5\ln\left(11\frac{h}{k_s}\right) \tag{4a,b}$$

in which u_* denotes shear velocity; and k_s denotes roughness height.

Sediment is classified in three layers: a subsurface layer, a surface layer, and a bedload layer. Their grain size distributions are described by dividing the whole grain size into several bins, or grain size groups, and specifying the volumetric fraction of each grain size group. The grain size is measured both in diameter D and in grain size ψ-scale,

$$\psi = \log_2(D), \quad D = 2^{\psi} \tag{5a,b}$$

In (5a,b) grain size D is in mm. If the full grain size range is divided into N bins, they will be bounded by N+1 grain sizes: D_0 (ψ_0), D_1 (ψ_1), D_2 (ψ_2), …, D_N (ψ_N), in which D_0 and D_N denote the finest and coarsest grain sizes.

The Exner equations of sediment continuity are:

$$(1-\lambda_p)B\frac{\partial\eta}{\partial t} + \frac{\partial Q_s}{\partial x} + 2\beta Q_s + \frac{1}{3\ln(2)}\beta Q_s\frac{p_1 + F_1'}{\Delta\psi_1} = q_{sl} \tag{6a}$$

$$\begin{aligned}(1-\lambda_p)B\left[\frac{\partial(L_aF_j)}{\partial t} + f_{Ij}\frac{\partial(\eta - L_a)}{\partial t}\right] + \frac{\partial(Q_sp_j)}{\partial x} + \beta Q_s(p_j + F_j') \\ - \frac{1}{3\ln(2)}\beta Q_s\left(\frac{p_{j+1} + F_{j+1}'}{\Delta\psi_{j+1}} - \frac{p_j + F_j'}{\Delta\psi_j}\right) = q_{sl}p_{lj}\end{aligned} \tag{6b}$$

in which λ_p denotes the porosity of the sediment deposit; t denotes time; Q_s denotes volumetric sediment transport rate; β denotes volumetric abrasion coefficient; p_j denotes the volumetric fraction of the j-th range within bedload (and p_1 is p_j for j = 1); F_j' is an estimate of aerial

fraction of the j-th range of the surface of the channel bed and approximated as identical to p_j for simplicity (and F_1' is F_j' for j = 1); $\Delta\psi_j = \psi_j - \psi_{j-1}$; q_{sl} denotes flux of sediment input per unit channel length from banks or tributaries; L_a denotes surface layer thickness, which is assumed to be a constant in the model; F_j denotes volumetric fraction of the j-th range within the surface layer; f_{Ij} denotes volumetric fraction of the j-th range within the sediment that is in exchange between the deposit and the bedload; p_{lj} denotes volumetric fraction of the j-th size range within the sediment input from banks and tributaries.

The model applies the surface-based bedload equation of Parker (1990), the detail of which is not discussed here in this report.

3. INSIDE THE PROGRAM

We will discuss several issues inside the computer program so that users can have the working knowledge with the computer code. Users do not plan to modify the computer code are advised to scan read Section 3.1 and skip Sections 3.2, 3.3, and 3.4.

3.1 Representation of channel networks

A channel network is represented in the model with the framework of Cui and Parker (1999). First a channel network is divided into several channel segments, termed as reaches in the model, with tributary junctions as their boundaries. Figure 1 is a schematic sketch of an example of channel network, where there are 15 channel segments (or reaches). In addition to the number of reaches, a two-dimensional array named JCT in the program delineate how the reaches are connected. For a reach numbered i, JCT(i,0) equals the reach number immediately downstream of Reach i. If Reach i is the downstream most reach then JCT(i,0) = 0. JCT(i,1) and JCT(i,2) are reach numbers immediately upstream of Reach i. If Reach i is the upstream end reach then JCT(i,1) = JCT(i,2) = 0. In the channel network shown in Figure 1, for example, JCT(5,0) = 2, JCT(5,1) = 8, JCT(5,2) = 9, JCT(1,0) = 0, JCT(12,1) = 0, and JCT(12,2) = 0.

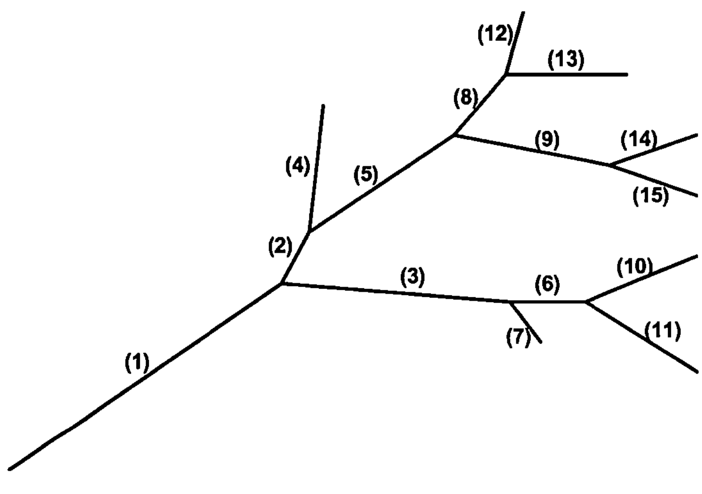


Figure 1. Schematic sketch of an example of a channel network

It needs to be noted that the numbering of the reaches is not unique. It is flexible to number a channel network as long as you follow the following two rules: (1) the numbers must range between 1 and N, in which N is the number of reaches; and (2) a downstream reach must have a reach number smaller than the reach numbers of its upstream reaches.

3.2 *Discretization of a channel network*

Each reach of a channel network is discretized into a number of small meshes for finite difference representation of the governing equations. Discretized nodes within any reach are numbered in an ascending order from the downstream end to the upstream end of a reach. Nodes in the entire channel network are numbered sequentially, beginning from Reach 1 and ending at the reach that has the highest reach number. In the computer program, the first and last nodes of Reach i are denoted as EndNode(i,1) and EndNode(i,2), respectively. By definition, the upstream end node of a downstream reach has the same location as the downstream end nodes of its immediate upstream reaches. In the channel network shown in Figure 1, for example, EndNode(5,2), EndNode(8,1), and EndNode(9,1) are all located at the junction of Reachs 5, 8, and 9.

3.3 *Identification and documentation of upstream boundaries*

In the computer program the upstream boundaries are identified and documented with two parameters: RNBC and NBC. RNBC is an upstream boundary serial number for each reach. If Reach i is not an upstream end reach, then RNBC(i) = 0. If Reach i is an upstream end reach, then RNBC(i) is a positive integer. NBC is the inverse of RNBC. If, for example, RNBC(i) = k, then NBC(k) = i. The upstream boundary serial number must be numbered sequentially from 1 to the number of reaches that have upstream boundaries. If both Reaches i and j are reaches with upstream boundaries and if i < j, then the upstream boundary serial number must satisfy RNBC(i) < RNBC(j). Table 1 gives the upstream end serial numbers for the channel network shown in Figure 1.

Table 1: RNBC and NBC values for the channel network shown in Figure 1

Reach Number (i)	4	7	10	11	12	13	14	15	Others
RNBC(i) = j	1	2	3	4	5	6	7	8	0
NBC(j) = i	4	7	10	11	12	13	14	15	n/a

It needs to be noted that parameters RNBC and NBC are handled entirely inside the computer code, and thus, users who are not interested in modifying the code do not need to comprehend this section.

3.4 *Identification and documentation of sediment input as point sources*

There are three mechanisms to feed sediment into the channel network: from the upstream end of the upstream most reaches, from point sources such as gully erosions or small tributaries that are not part of the channel network system for simulation, and from sediment pulses such as from landslides, mass wasting, or other events that occur episodically. Locations of point sources of sediment feed need to be mapped and assigned to node points. The documentation of locations of point sources is similar to the serial numbers of upstream end reaches discussed in Section 3.3. Two parameters, NABC and ABC are used in the program to keep record of the point source locations. If i is the node number where there is point source sediment input, then ABC(i) is an positive integer, which indicates the serial number of the point source. NABC is the inverse of ABC, i.e., if ABC(i) = j then NABC(j) = i. Point sources must be numbered consecutively beginning with 1. Point source serial number at a downstream node must be smaller than that for

a node at an upstream node. NABC and ABC are handled entirely inside the computer code, and thus, users who are not interested in modifying the code do not need to comprehend this section.

3.5 Constants that may need users attention

There are eleven constants that users may wish to modify for certain reasons. Those constant are all assigned in file constant.inc, which is included into the FORTRAN program. The program needs to be recompiled before any modifications to those parameters can take effect. The parameters are:

- g is acceleration of gravity with a value of 9.81 m/s^2. This parameter should not be modified unless the simulation is for a channel network on a different planet.
- α (alpha), with a default value of 0.00218, is a coefficient in the surface-based bedload equation of Parker (1990). It is recommended that this parameter not be modified unless you have compiling reasons to do so.
- β (beta), with a default value of 0.0951, is the hiding coefficient in the surface-based bedload equation of Parker (1990). It is recommended that this parameter not be modified unless you have compiling reasons to do so.
- τ^*_{rsgo} (taursgo), with a default value of 0.0386, is reference Shields stress in the surface-based bedload equation of Parker (1990). It is recommended that this parameter not be modified unless you have compiling reasons to do so. It is also recommended that this parameter be the first choice for adjustment if a calibration to the surface-based bedload equation of Parker (1990) is conducted.
- χ (chi), with a default value of 0.7, defines the grain size distribution of the interface that is in exchange between bed material and bedload in case of channel aggradation. The equation, given below

  $$f_{Ij} = \chi p_j + (1-\chi)F_j \tag{7}$$

  has been used by Hoey and Ferguson (1994) and Toro-Escobar et al. (1996). The default value of 0.7 for χ was derived by Toro_Escobar et al. (1996) from a set of large-scale laboratory experiment.
- D_k (Dk), with a default value of 2, defines how the roughness height is correlated to surface grain size distribution

  $$k_s = D_k D_{sg} \sigma_{sg}^{1.28} \tag{8}$$

  where D_{sg} denotes surface layer geometric mean grain size; and σ_{sg} denotes surface layer grain size geometric standard deviation.
- λ_p (poro), with a default value of 0.4, is the porosity of the sediment deposit. It needs to be noted that particles finer than 2 mm cannot be simulated with the model, and thus sand and finer will be counted for as pores in the sediment deposit.
- R, with a default value of 1.65, is submerged specific weight of sediment particles.
- L_a (La), with a default value of 0.5 m, is active layer (also called surface layer) thickness.

- F_{rn} (FRN), with a default value of 0.8, is a Froude number. Standard backwater equation (i.e., equation 1a) is applied if local Froude number is less than F_{rn}, and quasi-normal assumption (i.e., equation 1b) is applied if local Froude number is higher than F_{rn}. Modification to this parameter is not recommended.
- ΔX_f (DXF), with a default value of 10 m, defines the grid spacing for flow simulation. Reducing ΔX_f value will increase the stability of the calculation but increase the time needed to finish a run.

4. INPUT FILE PREPARATION

Eight input files need to be prepared before a simulation can be conducted. The input files are all self-documentary and easy to understand. It needs to be noted, however, that users must not attempt to modify the style of any of the input files. It is highly recommended that users save backup copies of workable input files before any modifications are made.

4.1 File bkkping.txt

```
Input data file bkkping.txt for program EFSalmon.f90
15   Number of Reaches
1     2     3      Name&of&Reach&1
2     4     5      Name&of&Reach&2
3     6     7      Name&of&Reach&3
4     0     0      Name&of&Reach&4
5     8     9      Name&of&Reach&5
6     10    11     Name&of&Reach&6
7     0     0      Name&of&Reach&7
8     12    13     Name&of&Reach&8
9     14    15     Name&of&Reach&9
10    0     0      Name&of&Reach&10
11    0     0      Name&of&Reach&11
12    0     0      Name&of&Reach&12
13    0     0      Name&of&Reach&13
14    0     0      Name&of&Reach&14
15    0     0      Name&of&Reach&15
1     52       Number of Nodes
2     11       Number of Nodes
3     34       Number of Nodes
4     12       Number of Nodes
5     26       Number of Nodes
6     11       Number of Nodes
7     25       Number of Nodes
8     15       Number of Nodes
9     24       Number of Nodes
10    35       Number of Nodes
11    31       Number of Nodes
12    16       Number of Nodes
13    25       Number of Nodes
14    14       Number of Nodes
15    17       Number of Nodes
```

List 1. A sample bkkping.txt file, documenting the channel network structure presented in Figure 1 and how each reach will be discretized.

File bkkping.txt stores information of channel network structure and discretization. A sample bkkping.txt file is given in List 1.

It can be seen from List 1 that the first row in bkkping.txt is a notation. The second row is the total number of reaches to be simulated followed with notations. The rest of bkkping.txt file consists two parts, each with N rows, where N is the total number of reaches. In the first part, the first column indicate reach number, the second and third columns specify reach numbers for the reach immediately upstream of the reach, and the forth column is a string of 36 characters or less, specifying the name of the reach. Note that space in the string is replaced with "&" for the reason that FORTRAN program has difficulties reading strings with spaces. The second part has three columns: the first column is reach number, the second column specifies the number of nodes to be used in simulation within that reach, and the last column is notation.

4.2 File sizeinfo.txt

Files sizeinfo.txt defines the discretization of grain size and specifies surface grain size distribution in each reach. List 2 is a sample sizeinfo.txt file where a number of rows have been omitted to save space.

```
Input data file Sizeinfo.txt for program EFSalmon.f90
    ... There are 8 rows of notations here!
Give the number of grain size subranges below:
6
Specify the grain size (in mm) that will bound the subranges. For example,
if you specified 7 subranges, you will need to give 8 grain sizes, from
finer to coarser. The finest grain size should be no finer than 2 mm.
4 8 16 32 64 128 256
--------------------------------------------------------------------
    ... There are 10 rows of notations here!
1       2
0.1 0 5 30 47 75 89 100
8.3 0 4 27 48 74 82 100
2       3
0.1 0 5 30 47 75 89 100
0.5 0 5 32 49 77 92 100
2.1 0 4 27 48 74 82 100
...There are more rows for reaches 3 through 14 here!
15      2
0.1 0 5 30 47 75 89 100
0.3 0 4 27 48 74 82 100
--------------------------------------------------------------------
End of file!
--------------------------------------------------------------------
```

List 2. A sample sizeinfo.txt file, documenting the discretization of grain size and specifying surface grain size distributions.

The first parameter to be specified in sizeinfo.txt is the number of grain size bins. If the grain size ranges between 4 and 256 mm, and will be discretized to 4-8, 8-16, 16-32, 32-64, 64-128, and 128-256 mm, then the number of grain size bins is 6. The next parameters to be entered to sizeinfo.txt are grain sizes that bounds the grain size bins, and you need one more grain size than the specified number of grain size bins. In the sample file given in List 2, there are 7 grain sizes while the number of bins was specified to be 6.

Surface grain size distributions for each reach are specified starting from Reach 1. This is done by first specifying reach number and the number of grain size distributions to be specified for the reach. In the example in List 2, for example, there are two grain size distributions for Reach 1, 3 for Reach 2, and 2 for Reach 15. Each location is then specified with a distance in km, which is

measured from the downstream end of that reach, followed by percent finer values associated with the grain sizes specified earlier. In List 2 for example, the grain size distributions for Reach 2 are specified at 0, 0.5, and 2.1 km upstream of the downstream end of Reach 2 (*i.e.*, the junction of Reaches 1, 2, and 3), and the grain size percent finer associated with 4, 16, 32, 64, 128, and 256 mm at 0.5 km upstream of the downstream end of Reach 2 are 0, 5, 32, 49, 77, 92, and 100%.

4.3 File discharge.txt

Discharge can be specified to any number of stations. An example of discharge.txt is given in List 3, where discharge record at 15 discharge stations are specified. Daily discharge, in cubic feet per second (cfs), is the only parameter to use imperial unit in the input files. Discharge stations can be numbered arbitrarily but data on the i-th column in file discharge.txt stores discharge record for station i. The last discharge at any station must be -1, which tells the program to go back to the beginning of the record.

```
Input data file "discharge.txt" for program EFSalmon.f90
Do not edit this file unless you know what you are doing!
Do not delete any explanatory text!
Discharge are given in cfs (cubic foot per second). This is the only Queen's
unit in all the input/output files.
The number of hydro-stations are defined in file geometry.txt. The number of
columns in this file must match the number of hydro-stations. Each station
takes one column with the first columnn representing station no. 1. Discharge
are given as daily average and each row represent one day.
The last row are given as -1's (again, the number of -1's should be equal the
number of hydro-stations). The program will come back and read from the begining
of the file once it encounters the -1's. Enter discharge record below the dashed
line.
-------------------------------------------------------------------------------
820  512  307  102  410  205  114  215  202  132  121  97   89   121  78
820  512  307  102  410  205  114  215  202  132  121  97   89   123  87
...More row for discharge record here!
55   32   15   4    9    8.5  5    23   26   13   14   22   2    18   31
-1   -1   -1   -1   -1   -1   -1   -1   -1   -1   -1   -1   -1   -1   -1
-------------------------------------------------------------------------------
End of file!
-------------------------------------------------------------------------------
```

List 3. sample discharge.txt file, documenting discharge at a number of hydrologic stations.

The number of record for each station must be identical, although you can have any number of discharge record. It is, however, recommended that you have at least several years of discharge record in order to conduct a simulation. Discharge on smaller tributaries of the channel network may not be always available. If that is the case, you need to come up with an estimated discharge record through whatever means appropriate. Typical measures to estimate discharge record include synthesizing, hydrologic simulation and transformation from similar basins.

4.4 File geometry.txt

File geometry.txt stores geometric information such as bed elevation and channel width for the nodes. It also specifies which discharge station to use, and whether a specific node has any point source sediment input. An example of file geometry.txt is given in List 4 below.

```
Input data file geometry.txt for program EFSalmon.f90
Do not delete this and any other lines. Do not use comma in this file!
A spreedsheet program in MS-Excel 2000 will be written for input data
modification and users are encouraged to use that program for handling
of all the input data in this file.
---------------------------------------------------------------------
The data are given for reaches starting from Reach 1. The 1st column is
serial number (node number within a reach) and the 2nd column is the
distance between the current node and the downstream end, in km. The
3rd column is channel width in meters. The 4th column is the unerodible
base elevation in meters. The 5th column is the initial thickness of
sediment deposition. The 6th column is an indicator as whether there
is additional sediment coming into the channel at the node (1 = yes
and 0 = no). Additional sediment might be coming from a tributary which
you are not directly modeling. The last column is the hydro-station
index.
---------------------------------------------------------------------
Reach No.     1  Name&of&Reach&1
 1  0.000000E+00  0.170000E+02  0.609600E+02  0.000000E+00  0  1  $$$
 2  0.196078E+00  0.170000E+02  0.615644E+02  0.000000E+00  0  1  $$$
...More rows for nodes 3 through 51 here!
52  0.100000E+02  0.170000E+02  0.882215E+02  0.269655E+01  0  1  $$$
---------------------------------------------------------------------
Reach No.     2  Name&of&Reach&2
 1  0.100000E+02  0.100000E+02  0.882215E+02  0.269655E+01  0  2  $$$
 2  0.101718E+02  0.100000E+02  0.889407E+02  0.261947E+01  0  2  $$$
...More rows for nodes 3 through 10 here!
11  0.117179E+02  0.100000E+02  0.957506E+02  0.193077E+01  0  2  $$$
---------------------------------------------------------------------
...More rows for Reachs 3 through 14 here!
Reach No.    15  Name&of&Reach&15
 1  0.208462E+02  0.600000E+01  0.173126E+03  0.000000E+00  0  15  $$$
 2  0.210385E+02  0.600000E+01  0.177185E+03  0.000000E+00  0  15  $$$
...More rows for Reaches 3 through 16 here!
17  0.239231E+02  0.600000E+01  0.243840E+03  0.000000E+00  0  15  $$$
---------------------------------------------------------------------
End of file!
---------------------------------------------------------------------
```

List 4. sample geometry.txt file, documenting geometric and other information for each node.

As indicated in List 4, information is specified for each reach, starting from Reach No. 1. The seven columns for each reach specify: (1). node number within the reach (counting from the downstream end), (2). distance in km measured from the downstream end of Reach 1, (3). bankfull width, (4). base elevation, (5). thickness of sediment deposit, (6). a 0/1 indicator to identify whether there is additional point source input at the node with 0 representing no and 1 representing yes, and (7). Hydrologic station associated with the node. There is an additional eighth column with a string "$$$" that is not read by the model. It is, however, recommended that you add those strings to your file as it is reserved for use by a graphic user-interface to be developed in the future if funding is available.

4.5 File maingrv.txt

File maingrv.txt specifies long-term average gravel supply at the upstream end of the upstream most reaches (e.g., Reaches 4, 7, 10, 11, 12, 13, 14 and 15 for the channel network shown in Figure 1). A sample maingrv.txt file corresponds to the channel network in Figure 1 is given in List 5 below.

```
Input data file maingrv.txt for program EFSalmon.f90
Do not delete this and any other explainatory lines. Always use the Excel
file for easy input unless you really know what is in this file.
------------------------------------------------------------------------
The gravel input from upstream end are in increasing sequence according to
reach number, each seperated with a dashed line. The input is given in
metric tons per annum for each grain size subrange. The reach number and
reach name, if any, are given on top of the input data as a single line.
------------------------------------------------------------------------
Reach No. 4 Name of Reach 4
 232.5
 592.5
 885
 2047.5
 2190
 1552.5
------------------------------------------------------------------------
Reach No. 7 Name of Reach 7
 81
 256.5
 436.5
 1174.5
 1422
 1129.5
------------------------------------------------------------------------
...More rows for Reaches 10, 11, 12, 13 and 14
Reach No. 15 Name of Reach 15
 232.5
 592.5
 885
 2047.5
 2190
 1552.5
------------------------------------------------------------------------
End of file!
------------------------------------------------------------------------
```

List 5. A sample adnlgrv.txt file, documenting long-term average gravel input at the upstream end of the upstream most reaches

Similar to other input files, file maingrv.txt is rather self-documentary. For each of the upstream most reaches, gravel input is given for each grain size bin specified earlier in file sizeinfo.txt. The reaches start from the lowest numbered upstream most reach to the highest numbered upstream most reach. Under each reach the i-th record is the long-term average annual gravel transport rate, in m^3/yr, for the i-th grain size bin specified in file sizeinfo.txt.

4.6 File adnlgrv.txt

File adnlgrv.txt stores long-term average gravel transport rates for additional point sources. A sample adnlgrv.txt file is given in List 6 below.

```
Input data file adnlgrv.txt for program EFSalmon.f90
Do not delete this and any other explainatory lines. An Excel program will
be developed for creating/editing this file.
--------------------------------------------------------------------------
The gravel input from additional nodes are in increasing sequence according
to reach number and node number, each separated with a dashed line. The
input
is given in metric tons per annum for each grain size subrange. The Reach
and node numbers and reach name, if any, are given on top of the input data
as a single line.
--------------------------------------------------------------------------
Reach 1 node 16 Name of Reach 1
 34.81
 58.02
 58.02
 63.83
 34.82
 0.48
--------------------------------------------------------------------------
Reach 1 node 19 Name of Reach 1
 13.92
 23.21
 23.21
 25.53
 13.92
 0.19
...More rows for other nodes with point source sediment input!
--------------------------------------------------------------------------
End of file!
--------------------------------------------------------------------------
```

List 6. A sample adnlgrv.txt file, documenting long-term average gravel input at point sources

File adnlgrv.txt is very similar in structure to that of file maingrv.txt and thus, no further discussion is given here in this report.

4.7 File misc.txt

The following parameters are stored in file misc.txt: volumetric abrasion coefficient, time increment to be used in the simulation, number of years the simulation should be conducted, and a parameter that will define the relation between sediment input and discharge, as discussed below.

In *EFSalmon*, sediment inputs from the upstream end of the upstream most reaches and from point sources are assumed to follow the following relation.

$$Q_s = aQ_w^{\ b} \tag{9}$$

The parameter you need to specify is b in equation (9). In general, parameter b ranges between 1 and 3 in most cases. Parameter a will be derived based on the value of parameter b, the long-term average supply, and the discharge record within the program.

File misc.txt is very simple and self-documentary, and thus, no further discussion is given here in this report.

4.8 File pulses.txt

File pulses.txt documents sediment pulses that would occur in the channel network within the duration of the run. A sample pulses.txt file is given in List 7 below. File pulses.txt is adequately self-documented, and no further discussions are given here in this report.

```
Input data file pulses.txt for program EFSalmon.f90
This file stores everything that does not fit anywhere else. More variables
may be added to this file as the code develops.
--------------------------------------------------------------------------
Enter the number of sediment pulses that would occur during the period of
your simulation.
   3
Next you will be asked to describe each sediment pulse in a chronological
order. The information is arranged in the following way: the time (month
and year numbers in the same row, separated by spaces) when the sediment
pulse is introduced, counting from the begining of the simulation (month
0 and year 0); reach number where the sediment pulse is introduced, in one
row; the coordinates of the downstream end and upstream end of the sediment
pulse, both measured from the downstream end of the reach (distances to the
next junction), in km and in the same row; total volume, including the
pores, in cubic meters and in one row; and percent finers of the sediment
pulses associated to the grain sizes specified in sizeinfo.txt, in one row
and separated by spaces. Separate each sediment pulse with a dashed line,
and you must have the same number of pulses as specified in line 7 of this
file.
--------------------------------------------------------------------------
   3   0     (month  year)
   3         (reach number)
   0.2  1.1  (distances to the downstream junction)
   48000.0       (volume of the pulse, including pores)
   0   5   30  47  75  89  100
--------------------------------------------------------------------------
   5   1     (month  year)
   1         (reach number)
   1.2  5.1  (distances to the downstream junction)
   480000.0        (volume of the pulse, including pores)
   0   5   30  47  75  89  100
--------------------------------------------------------------------------
   5   1     (month  year)
   7         (reach number)
   0.2  1.1  (distances to the downstream junction)
   48000.0       (volume of the pulse, including pores)
   0   5   30  47  75  89  100
--------------------------------------------------------------------------
End of file!
--------------------------------------------------------------------------
```

List 7. A sample pulses.txt file, documenting sediment pulses that would occur within the duration of the run.

5. OUTPUT FILE

Results of the simulation are saved in file results.txt. File results.txt is self-documented and do not need further explanations. The large amounts of data in the file, however, make it very difficult to present the results. To overcome the difficulty, an Excel-VBA program, *EFSalmonOut.xls* is provided to extract results into six Excel files. Results include: bed

elevation, thickness of sediment deposit, surface geometric mean grain size, surface grain size geometric standard deviation, subsurface geometric mean grain size, and subsurface grain size geometric standard deviation. *EFSalmonOut.xls* is user-friendly and no manual is needed to extract information from file results.txt.

During an *EFSalmon* simulation, the prompt will ask the user to chose results printing intervals, including annual, bi-annual, semi-annual, quarterly, bi-monthly and monthly. It is suggested that results should be printed sparsely (e.g., no more frequent than quarterly) for long-term simulations. This is because an Excel workbook has only 256 columns, which limits the number of results that can be handled by *EFSalmonOut.xls*.

6. ZERO PROCESS

There are enormous amount of uncertainties in input data in sediment transport modeling. Coupled with the immaturity of sediment transport theories and modeling techniques, there are usually relatively large errors in the simulation results if the input data and simulation are not handled carefully. One of the techniques of reducing the relative errors in a sediment transport simulation is to establish a quasi-equilibrium background condition with a zero process prior to the intended simulation. The basic concept of the zero process is that rivers are normally in a short-term (~100 years) quasi-equilibrium state, i.e., a river may aggrade or degrade from year to year, but average over a relatively long period of time (e.g., several years) the cumulative change in bed elevation is minimal. During a zero process the model is run repeatedly so as to bring the system to a quasi-equilibrium state. Following the zero process certain input data will be modified automatically in correspondence to the quasi-equilibrium state, and the modified input files will be used for subsequent simulations.

7. SAMPLE RUN

A sample run is conducted for the channel network shown in Figure 1. The primary purpose of this sample run is to debug the model and test whether the model behaves as expected. All the input files and results for this sample run have been provided at an earlier date. Here only bed elevation, surface geometric mean grain size and subsurface geometric mean grain size for reach 1 are presented in Figures 2, 3, and 4, respectively. In Figure 2, a sediment pulse is introduced into the reach at 17 months into the run. Due to the relatively coarse grain size of the sediment pulse, evidenced in Figure 4, it evolved relatively slowly over the next 3 years. In time, the sediment pulse itself becomes progressively thinner, while a sediment delta moves in from the upstream. The sediment delta joins the initial sediment pulse within 5 years into the run.

In Figure 3, it is evident that surface layer becomes finer with the introduction of the sediment pulse that covers the original coarse surface layer. In time a new surface layer develops and the bed over the sediment pulse becomes significantly coarser. At 5 years into the run, the surface grain size over the sediment pulse area begins to become slightly finer because the upstream finer sediment begins to move in.

Figure 4 indicates that the pulse sediment is coarser than the ambient subsurface sediment. The subsurface grain size in the sediment pulse remains coarser throughout the run.

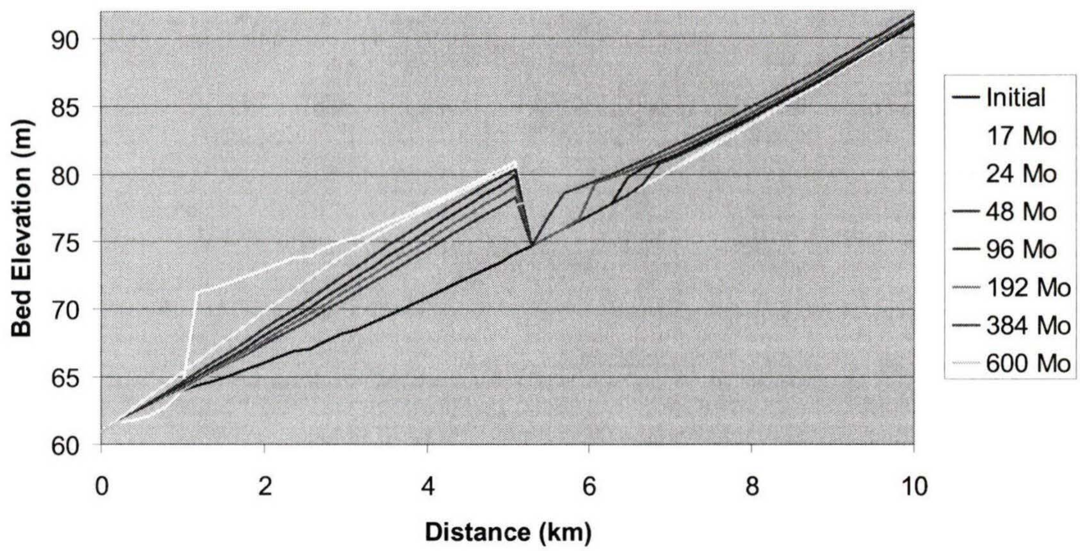


Figure 2. The evolution of a sediment pulse in Reach 1. The initial sediment pulse is introduced at 17 month. The pulse itself disperses, i.e., becomes progressively thinner in time. At the mean time, a sediment delta moves in from the upstream and joins the sediment pulse.

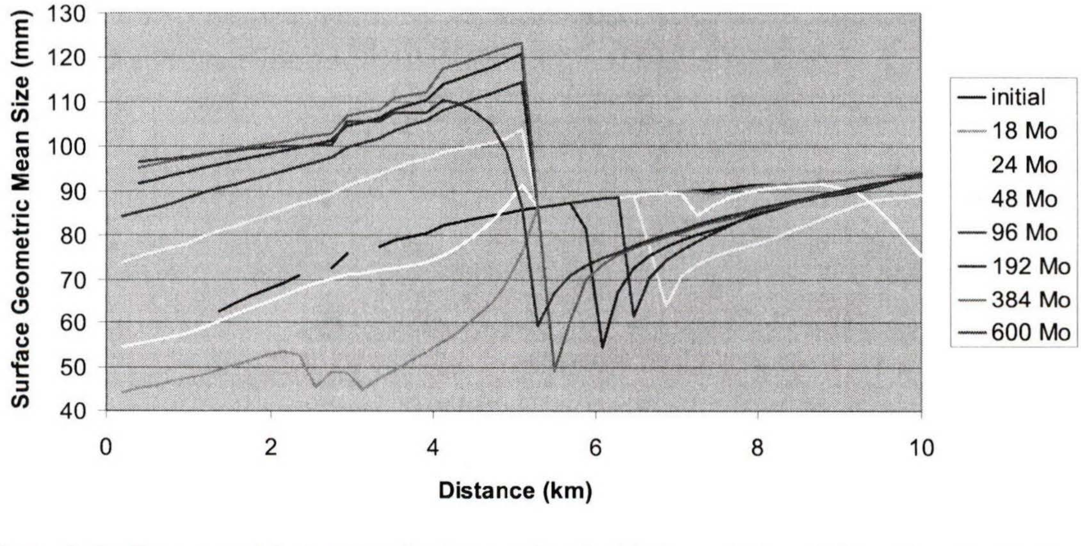


Figure 3. Surface geometric mean grain size associated with the evolution of the sediment pulse in Reach 1. The gap in the initial grain size profile indicates bedrock exposure.

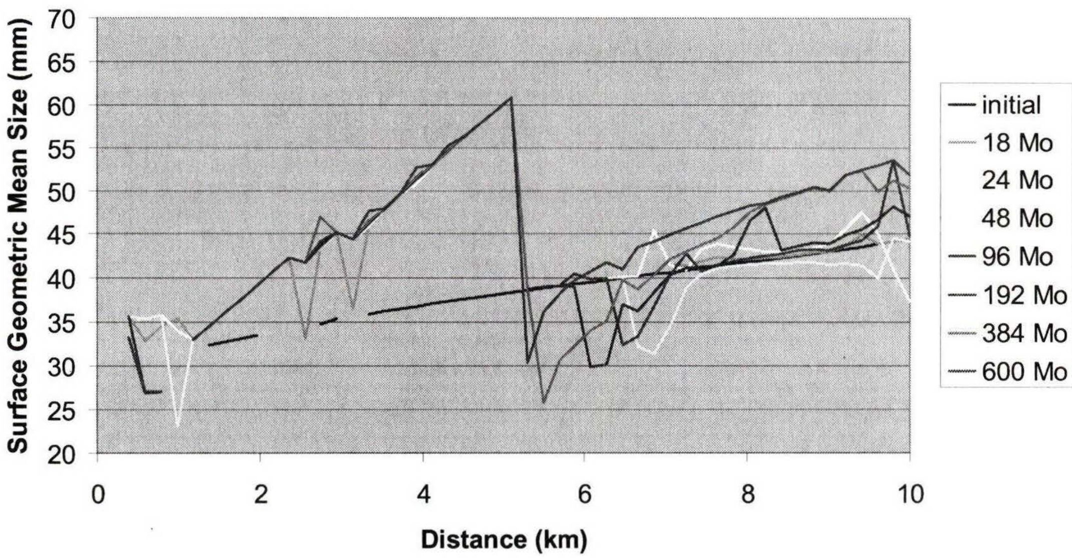


Figure 4. Subsurface geometric mean grain size associated with the evolution of the sediment pulse in Reach 1. The gap in the initial grain size profile indicates bedrock exposure.

REFERENCES

Cui, Y., and Parker, G. (2005) Numerical model of sediment pulses and sediment supply disturbances in mountain rivers, *Journal of Hydraulic Engineering*, to appear in the August issue.

Cui, Y., Parker, G., Pizzuto, J., and Lisle, T. (2003) Sediment pulses in mountain rivers. Part II: comparison between experiments and numerical predictions. *Water Resources Research*, 39(9), 1240, doi: 10.1029/2002WR001805. Cui and Parker (1999)

Cui, Y., Dietrich, W.E., and Parker, G. (2001) Routing bedload sediment through river networks draining steep uplands. *American Geophysical Union Fall Meeting*, San Francisco.

Cui, Y., and Parker, G. (1999) Sediment transport and deposition in the Ok Tedi-Fly River system, Papua New Guinea: the modeling of 1998-1999. *Technical Report*, St. Anthony Falls Laboratory, University of Minnesota, available on the web (accessed on May 22, 2005) at http://www.oktedi.com/reports/reports/15/MWMP_Sediment_model.pdf.

Hoey, T. B., and Ferguson, R. I. (1994) Numerical simulation of downstream fining by selective transport in gravel bed rivers: Model development and illustration. *Water Resources Research*, 30, 2251-2260.

Parker, G. (1990) Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research*, 28(4), 417-436.

Parker, G. (1991a) Selective sorting and abrasion of river gravel. I: Theory. *Journal of Hydraulic Engineering*, 117(2), 131-149.

Parker, G. (1991b) Selective sorting and abrasion of river gravel. II: Application. *Journal of Hydraulic Engineering*, 117(2), 150-171.

Toro-Escobar, C.M., Parker, G., and Paola, C. (1996) Transfer function for the deposition of poorly sorted gravel in response to streambed aggradation. *Journal of Hydraulic Research*, 34(1), 35-54.

7 APPENDIX B: COMPARISON OF METHODS FOR ESTIMATING STREAM CHANNEL GRADIENT USING GIS, *PowerPoint presentation by Nagel et al. (2006)*

Comparison of Methods for Estimating Stream Channel Gradient Using GIS

David Nagel, John Buffington, and Daniel Isaak

USDA Forest Service, Rocky Mountain Research Station
Boise Aquatic Sciences Lab

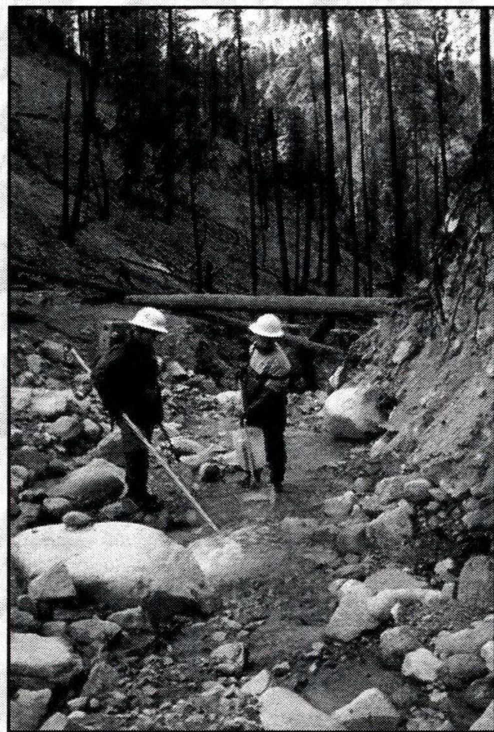
Boise, ID

September 14, 2006

Special thanks to Sharon Parkes….

BOISE AQUATIC SCIENCES LAB

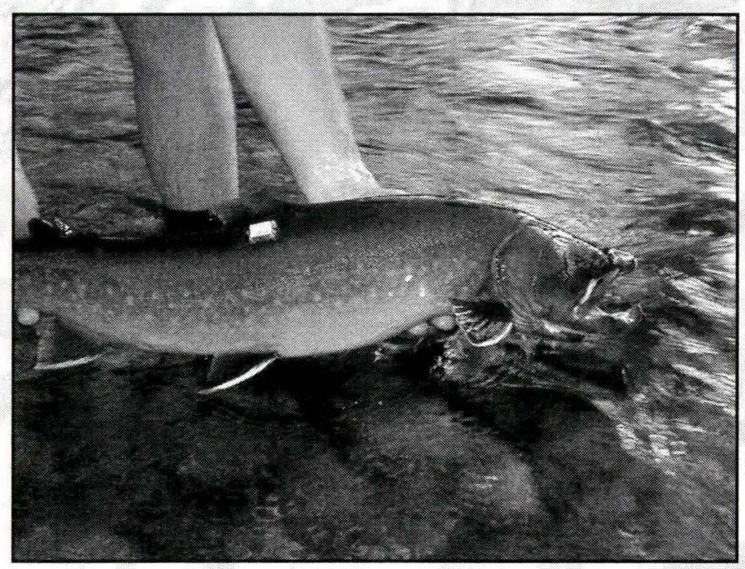
RMRS

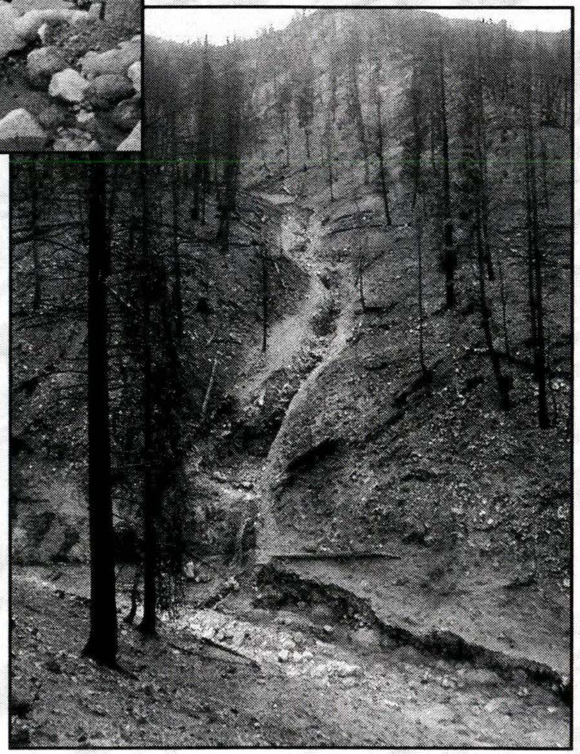


FOREST SERVICE

U S

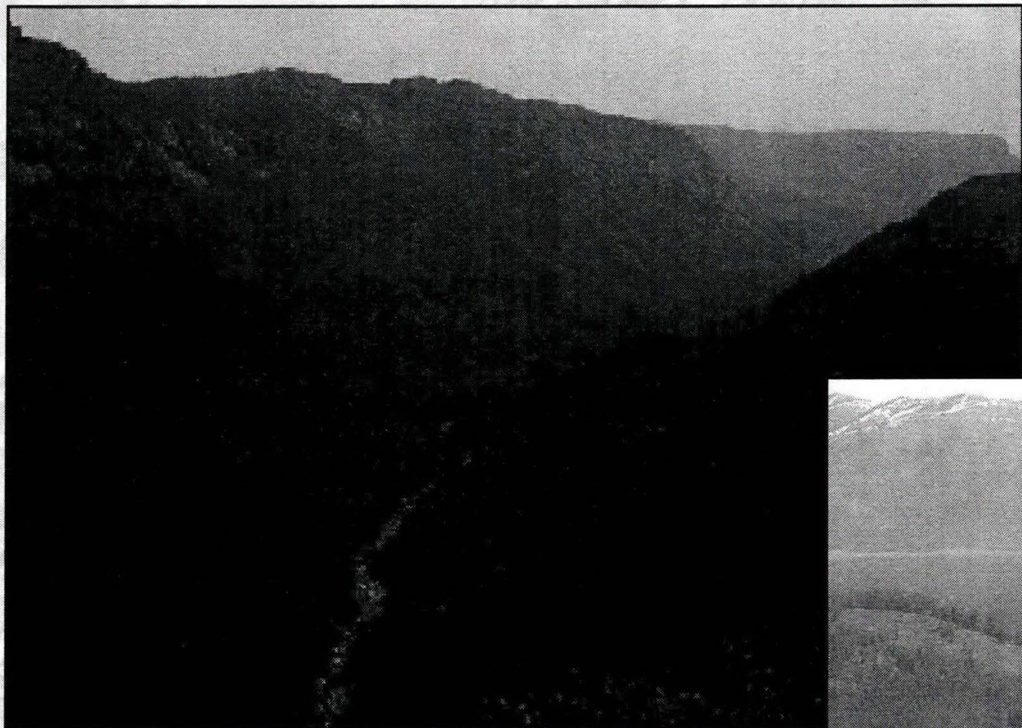
DEPARTMENT OF AGRICULTURE





Stream Channel Gradient

Rate of elevation change

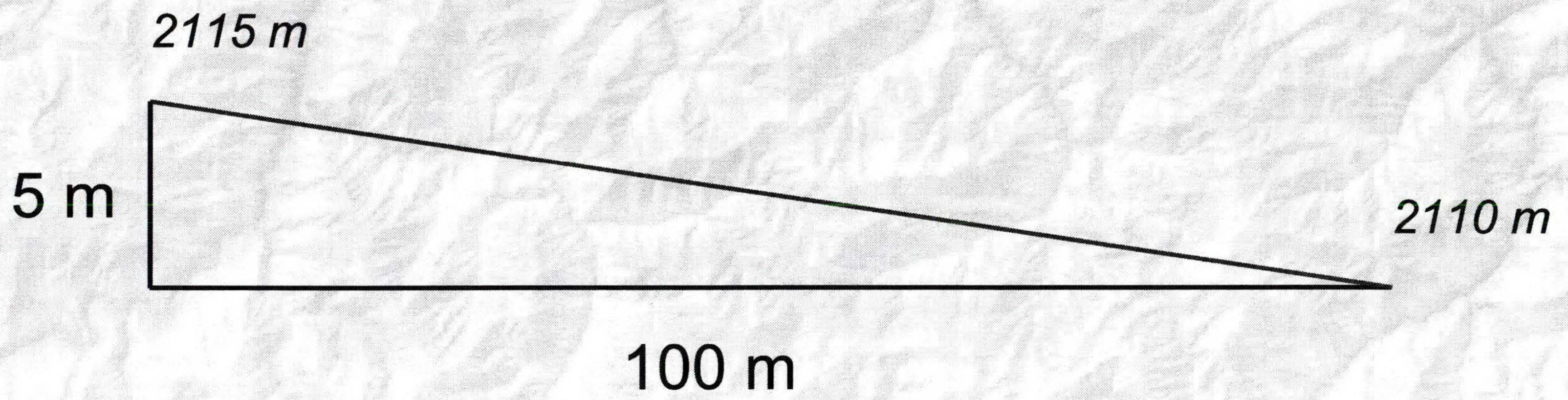


High

Low

Computing Gradient

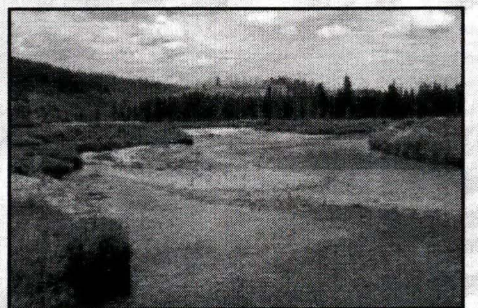
Rise / Run = Slope



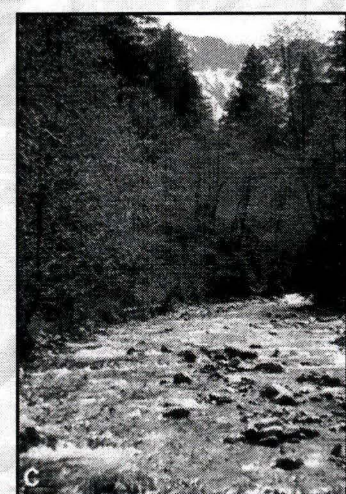
5 / 100 = .05 = 5% slope

Reasons for Modeling Stream Gradient

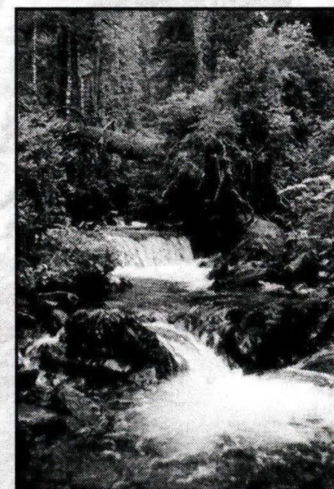
- Predictor of channel morphology



Pool-riffle
1%



Plain-bed
3 - 4%



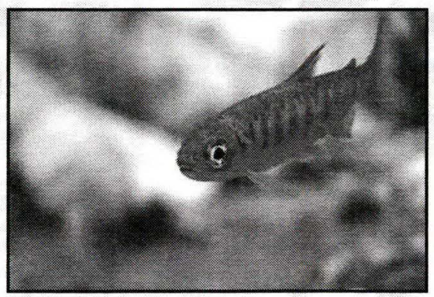
Step-pool
10%

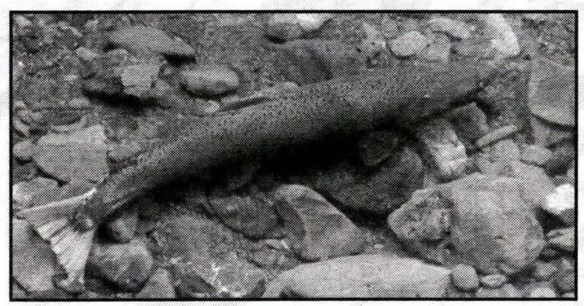
Reasons for Modeling Stream Gradient

- Estimate distribution of aquatic organisms

*"**Channel gradient** and channel morphology appeared to account for the observed differences in salmonid abundance, which reflected the known preference of juvenile coho salmon Oncorhynchus kisutch for pools."*

- Hicks, Brendan J. and James D. Hall, 2003





Reasons for Modeling Stream Gradient

- Predict debris flow transport and deposition

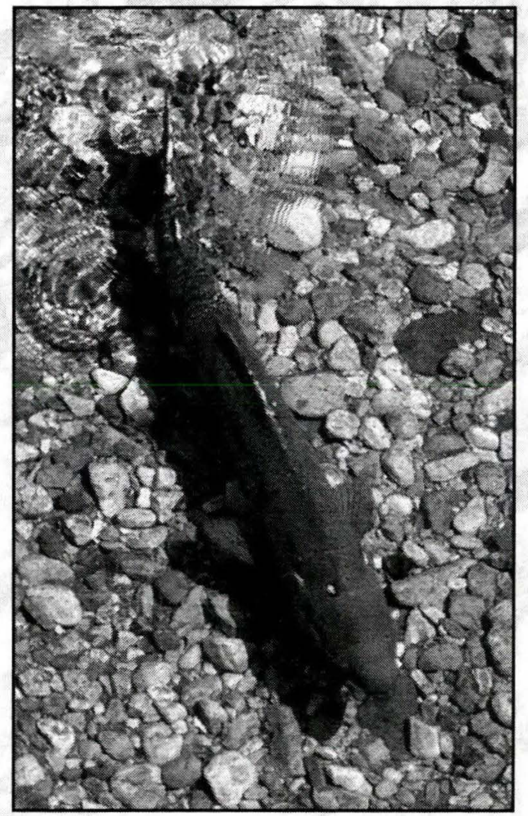
"Transportation and deposition of material in confined channels are governed primarily by water content of debris, channel gradient, and channel width."

- Fannin, R. J and T. P. Rollerson, 1993

Our Purpose for Modeling Stream Gradient

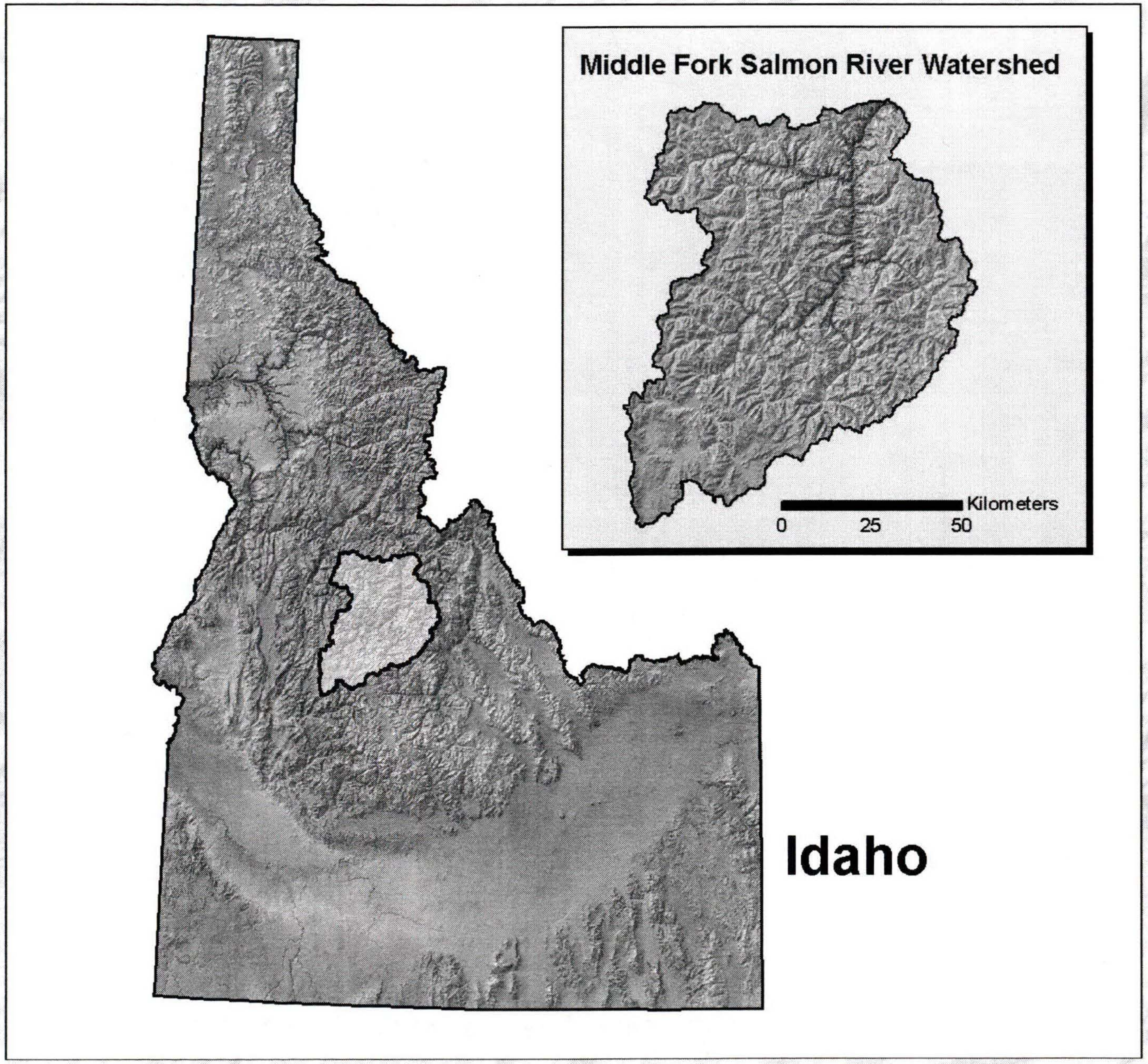
- Estimate stream bed grain size to identify salmon spawning habitat

$$Grain\ Size = \frac{1000 \rho g h S}{(\rho_s - \rho) g \tau *} = \frac{1000 \rho \left(cA^f S\right)^{1-n} \left(aA^b\right)^n}{(\rho_s - \rho) k}$$



S = channel slope

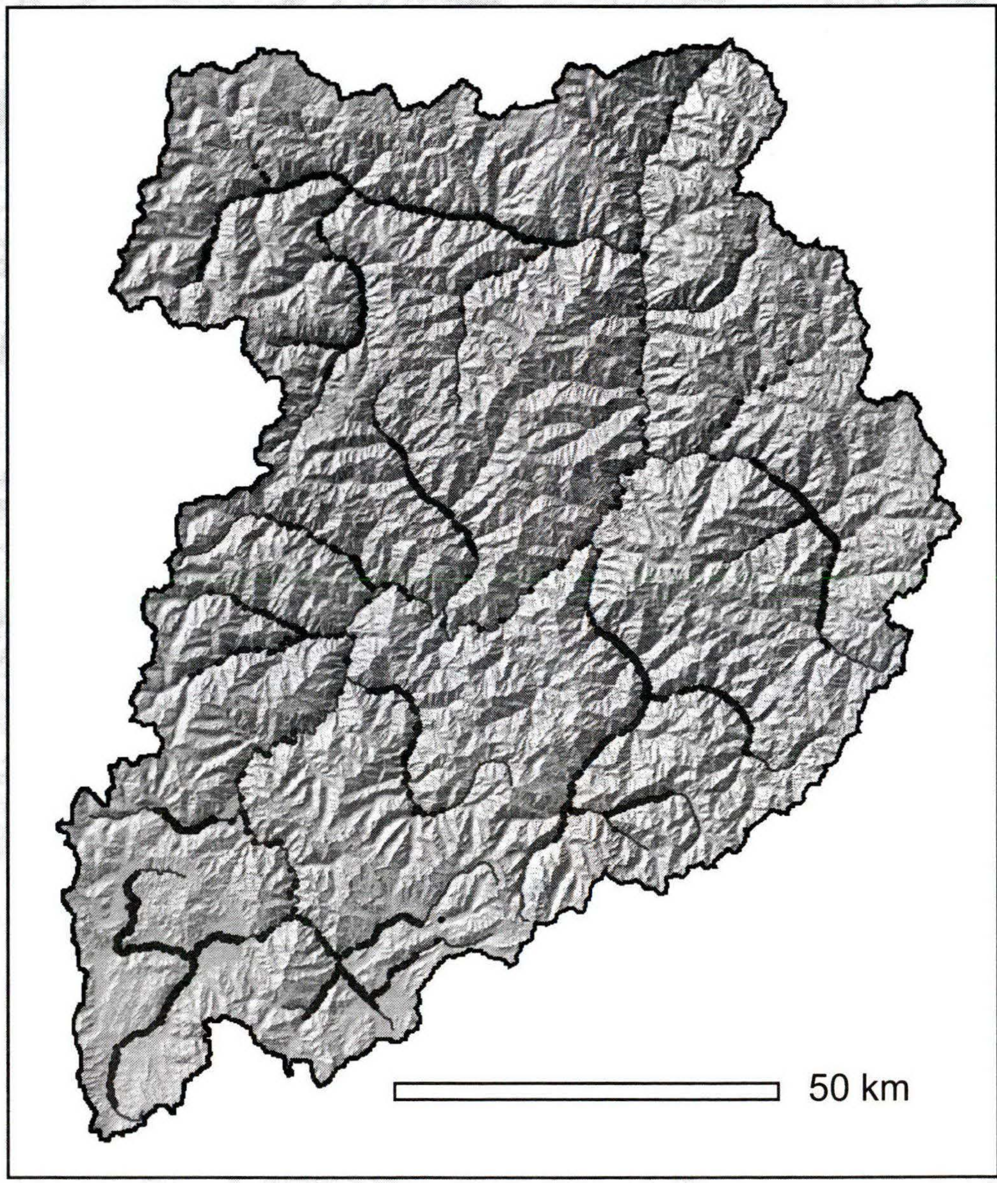
Grain size 16 – 51 mm



Study Area

10,000 km of rivers and streams

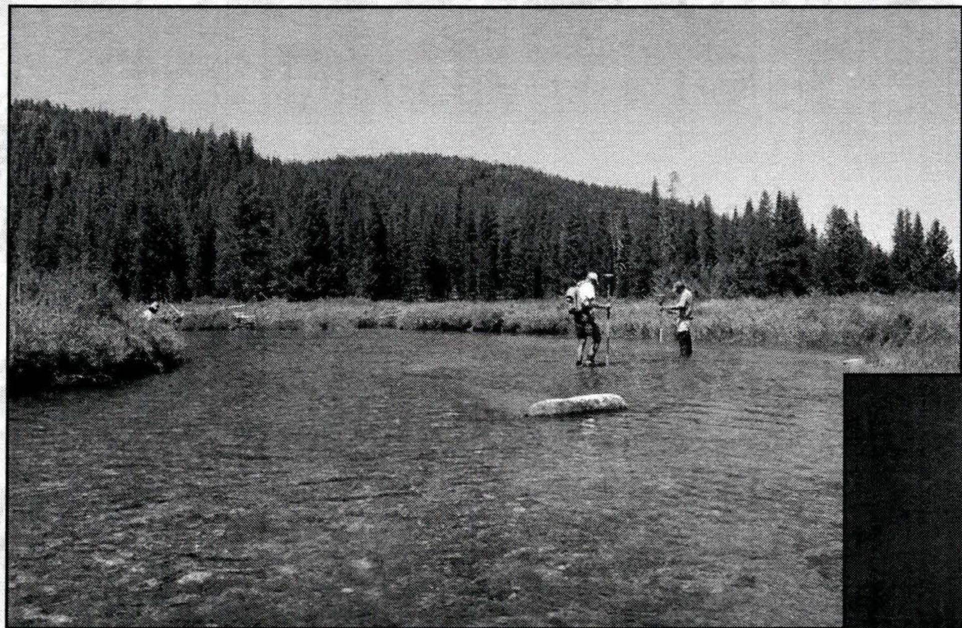
Chinook Salmon Spawning Sites 1995 - 2004



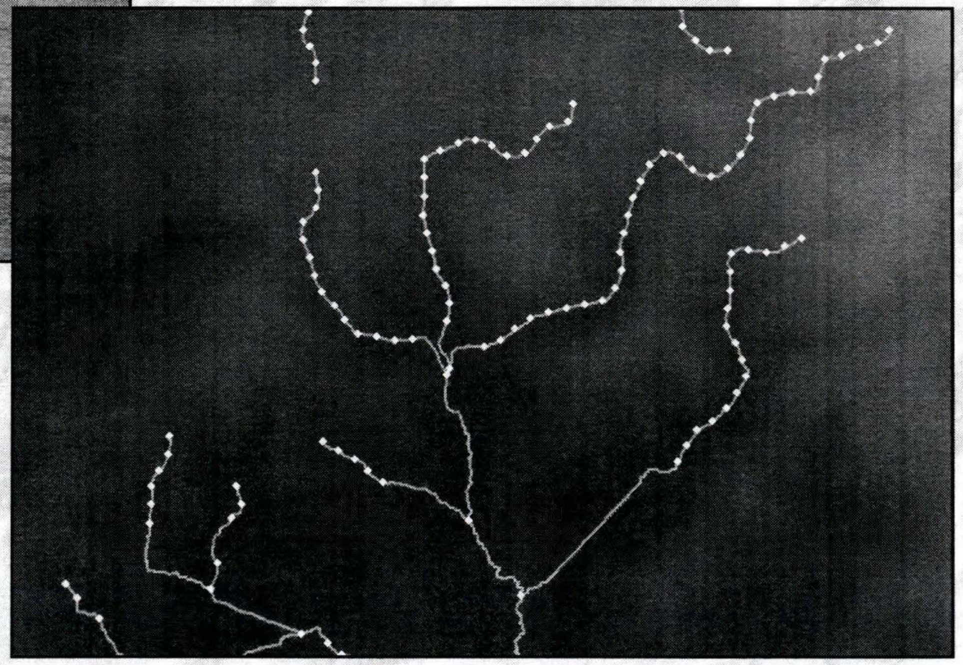
Research questions

1) Where are the optimum spawning sites?
2) Where might spawning expand if populations increased to historical levels?
3) Can grain size prediction be applied elsewhere?

Measuring Gradient



Directly



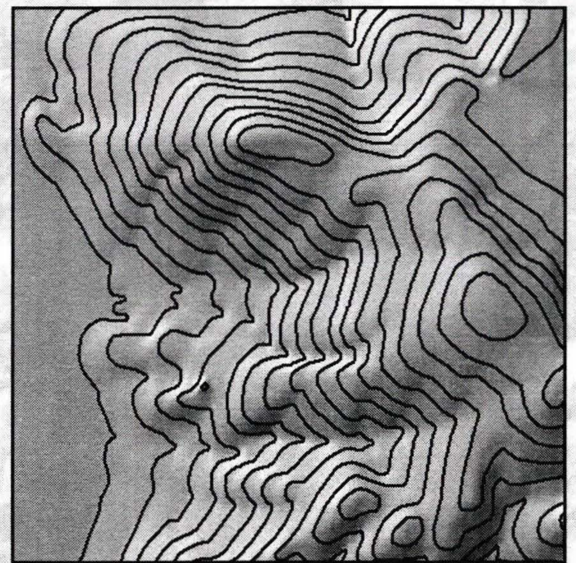
Remotely

Digital Data

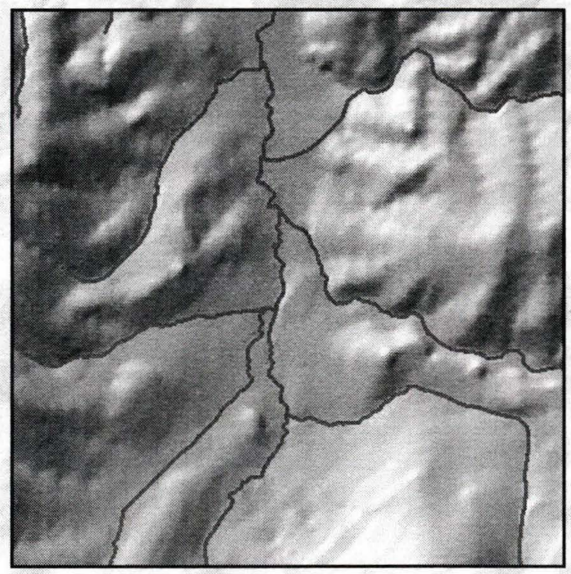
Some preliminary information

Necessary Data

1) Elevation - to compute rise

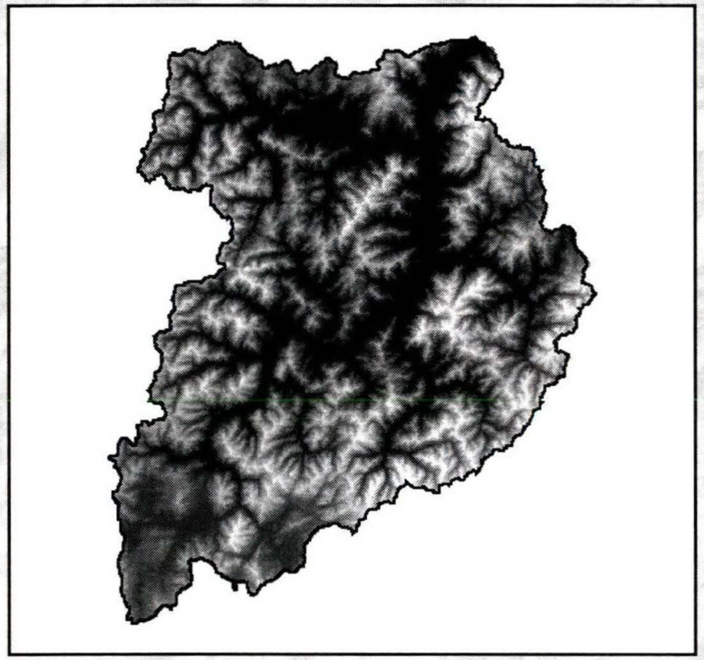


2) Stream lines - to compute run



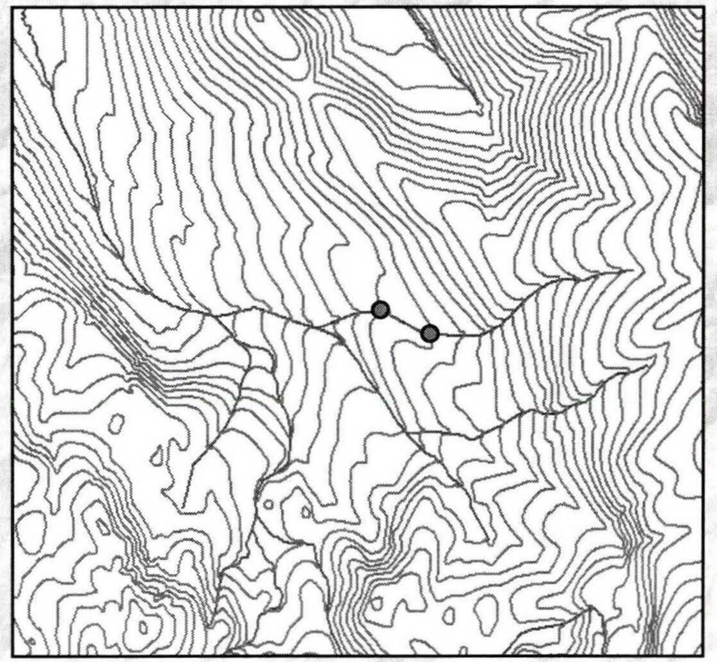
Choose Elevation Data

Digital Elevation Model (DEM)



USGS National Elevation Dataset (NED)

Contour lines

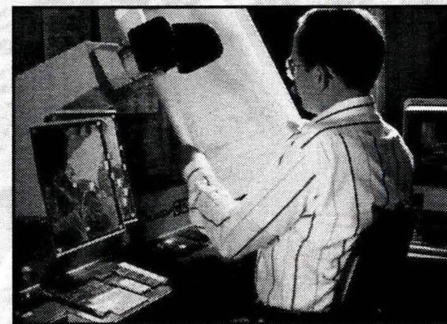


USGS 1:24,000 scale

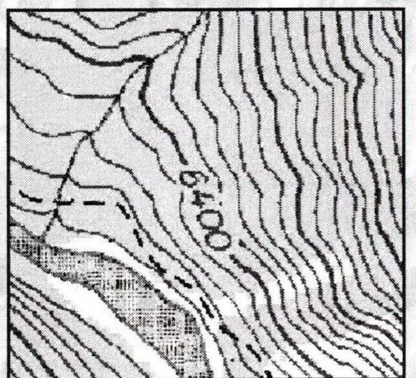
DEM Production Process

1) Aircraft

2) Aerial photo



3) Stereo plotter

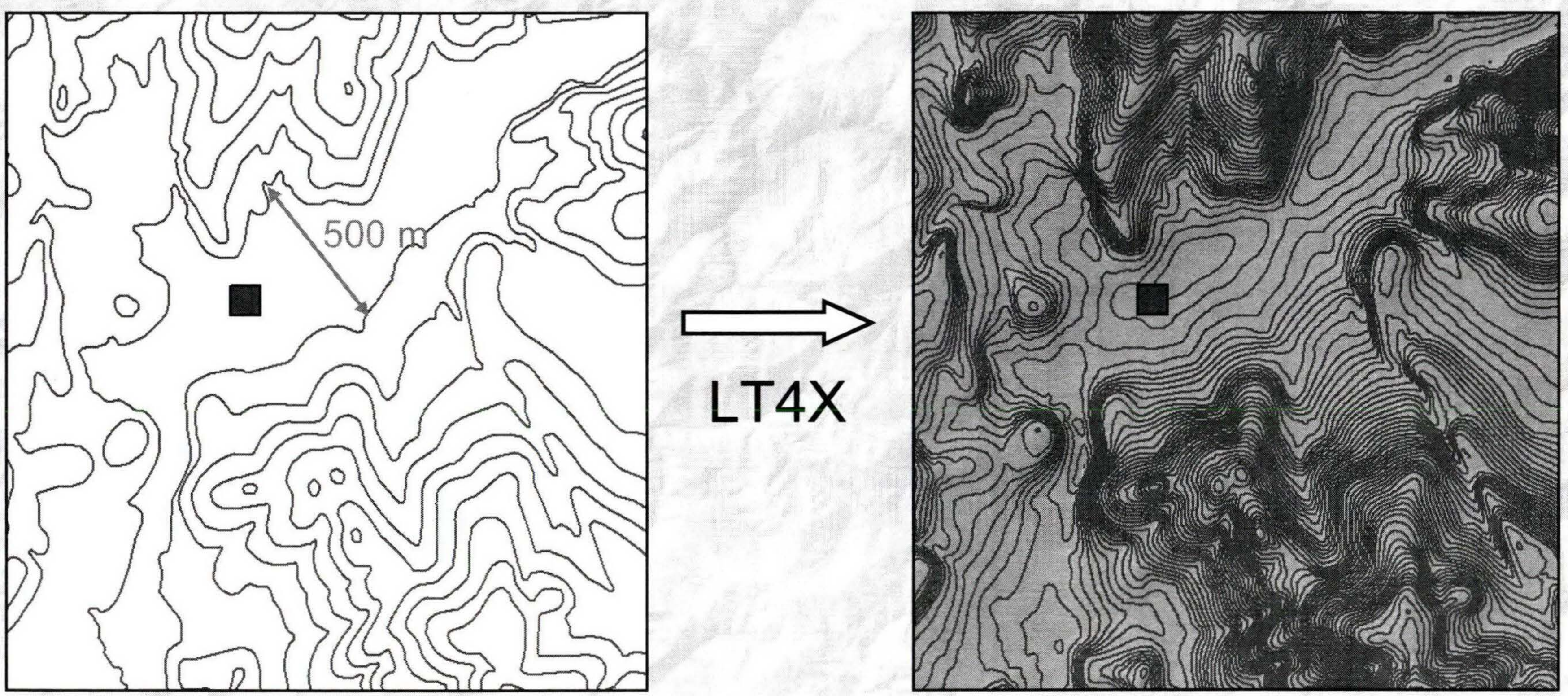


4) Map production

5) Scan and tag

6) LT4X

Original Contours and 10 m DEM Model

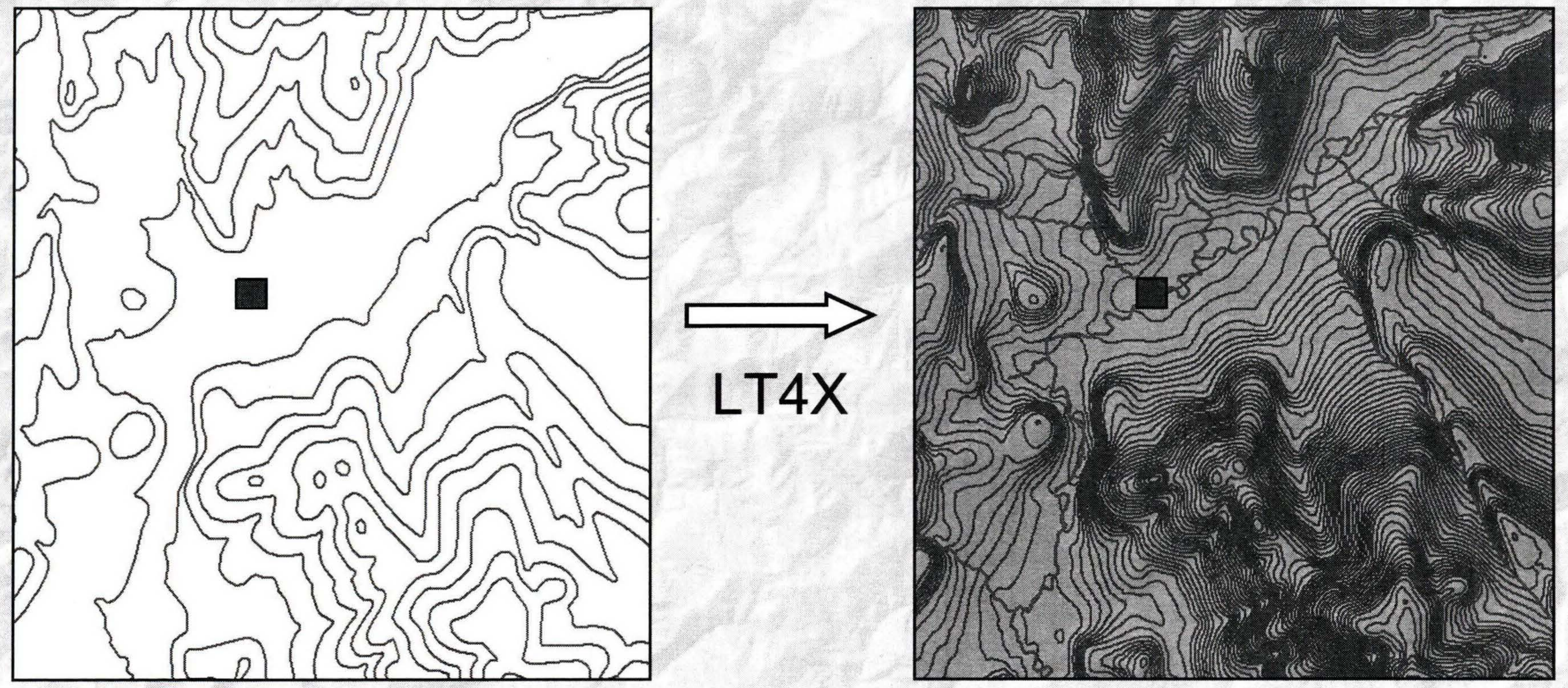


Original 40' contours

2 m contours derived from 10 m DEM

Blue box = 100 m x 100 m

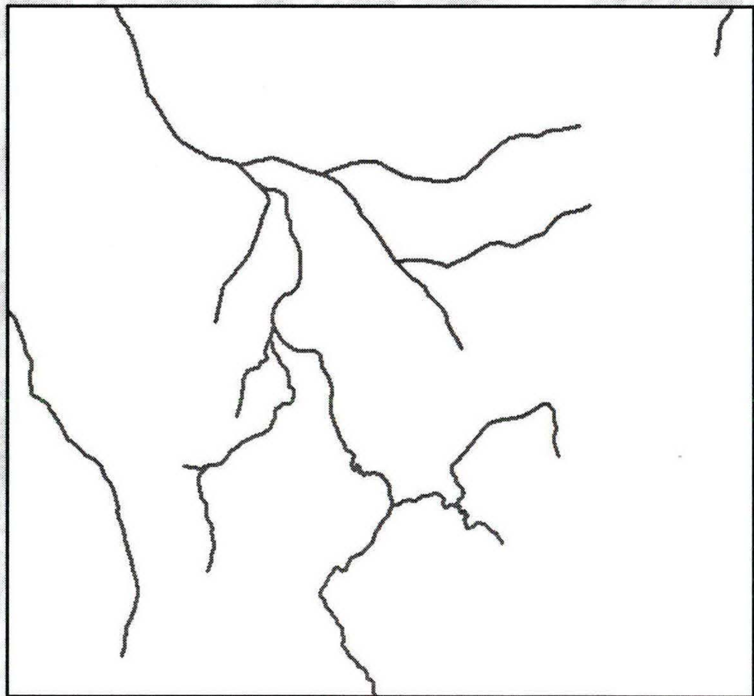
Original Contours and 10 m DEM Model



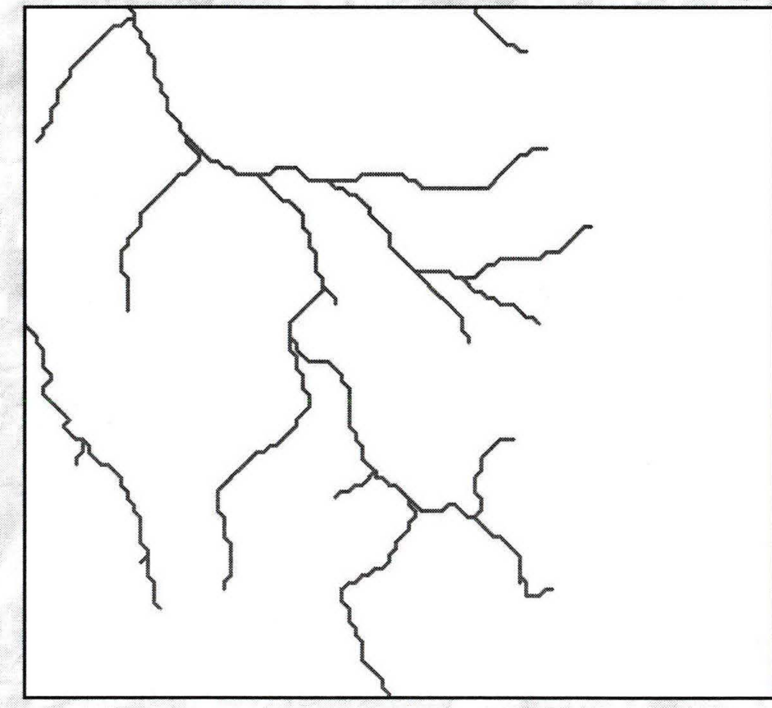
Original 40’ contours

2 m contours derived from 10 m DEM

Choose Stream Line Data

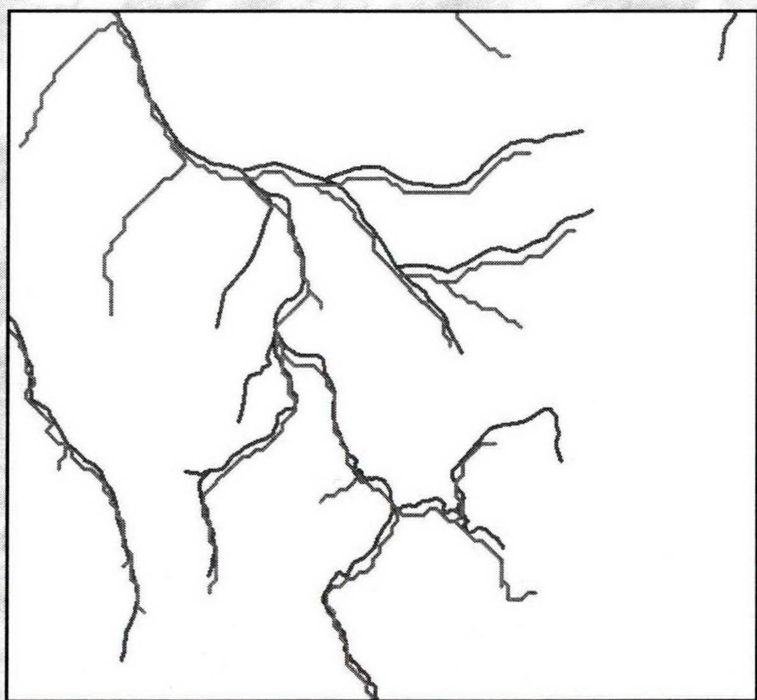


National Hydrography Dataset (NHD)

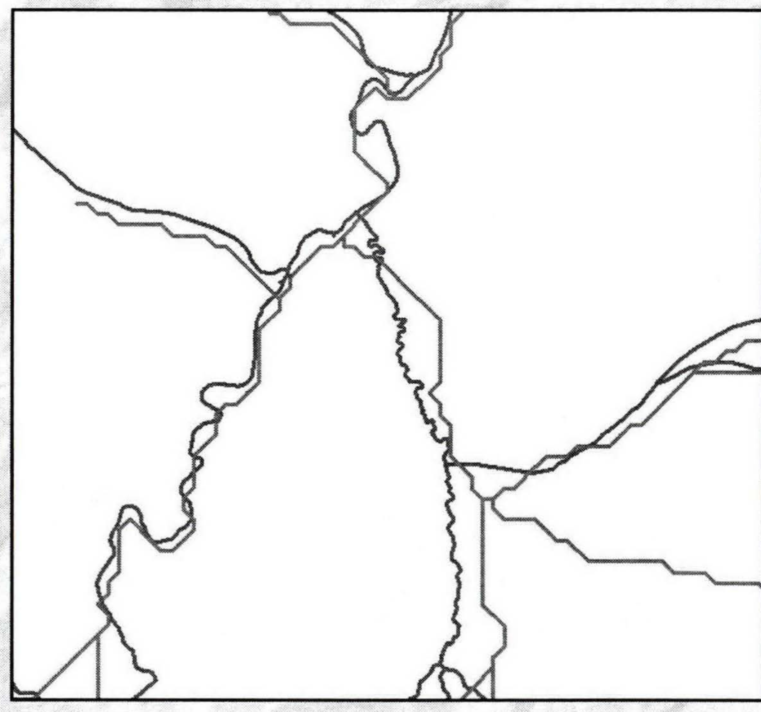


Synthetic stream lines

NHD and Synthetic Comparison

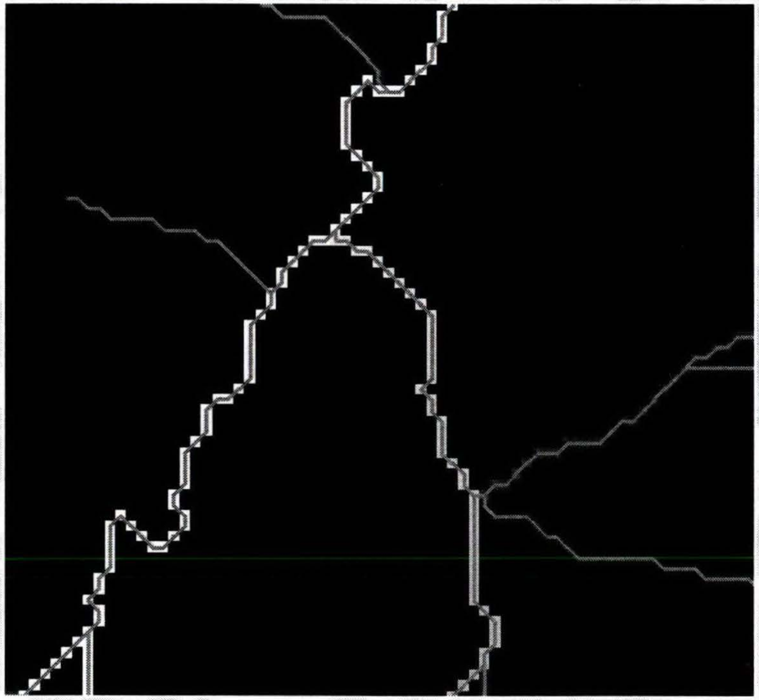


Higher gradient



Low gradient

Synthetic Streams "Fit" the DEM

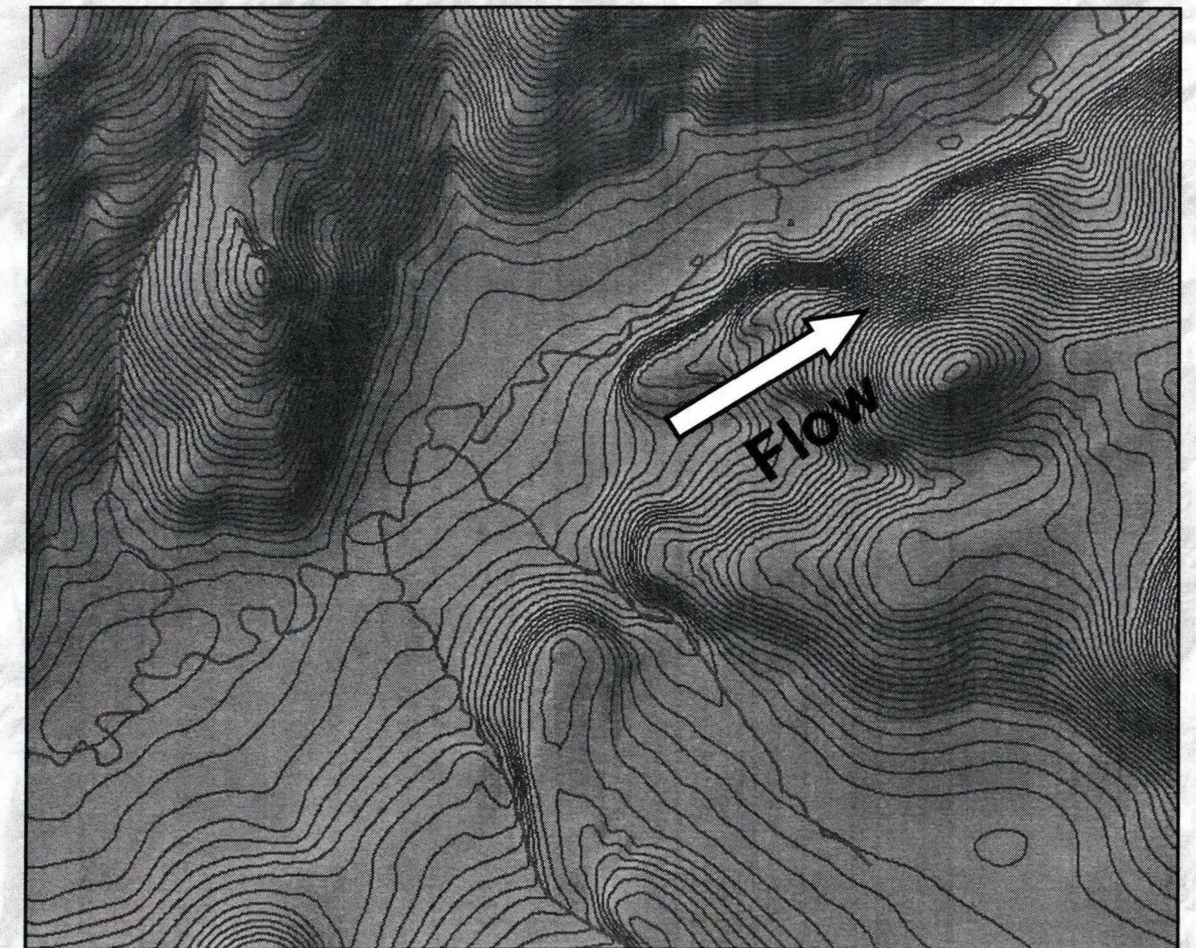


Synthetic streams follow the flow accumulation path and fall within the DEM channel

NHD streams often fall on DEM side slopes

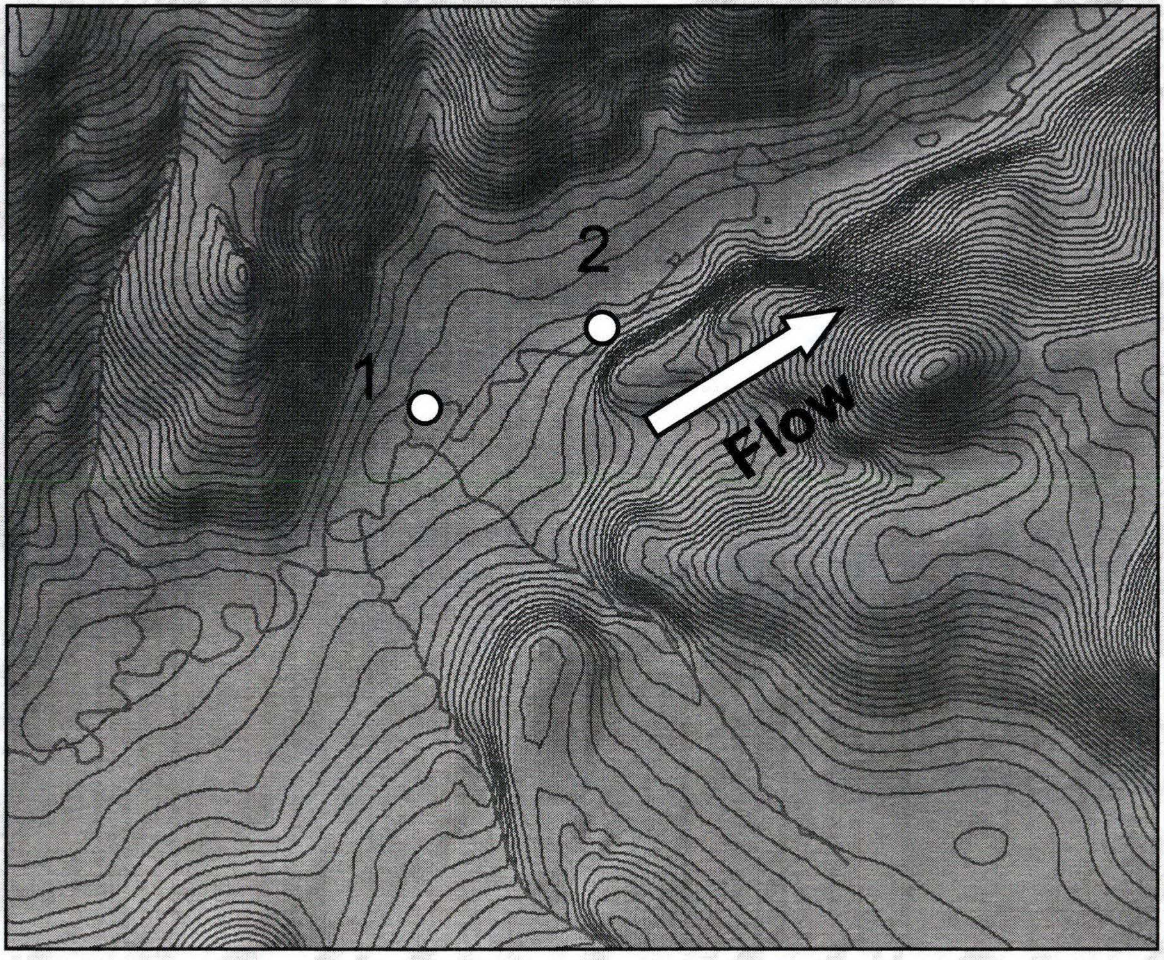
NHD and 10 m DEM Contours

2 m interval

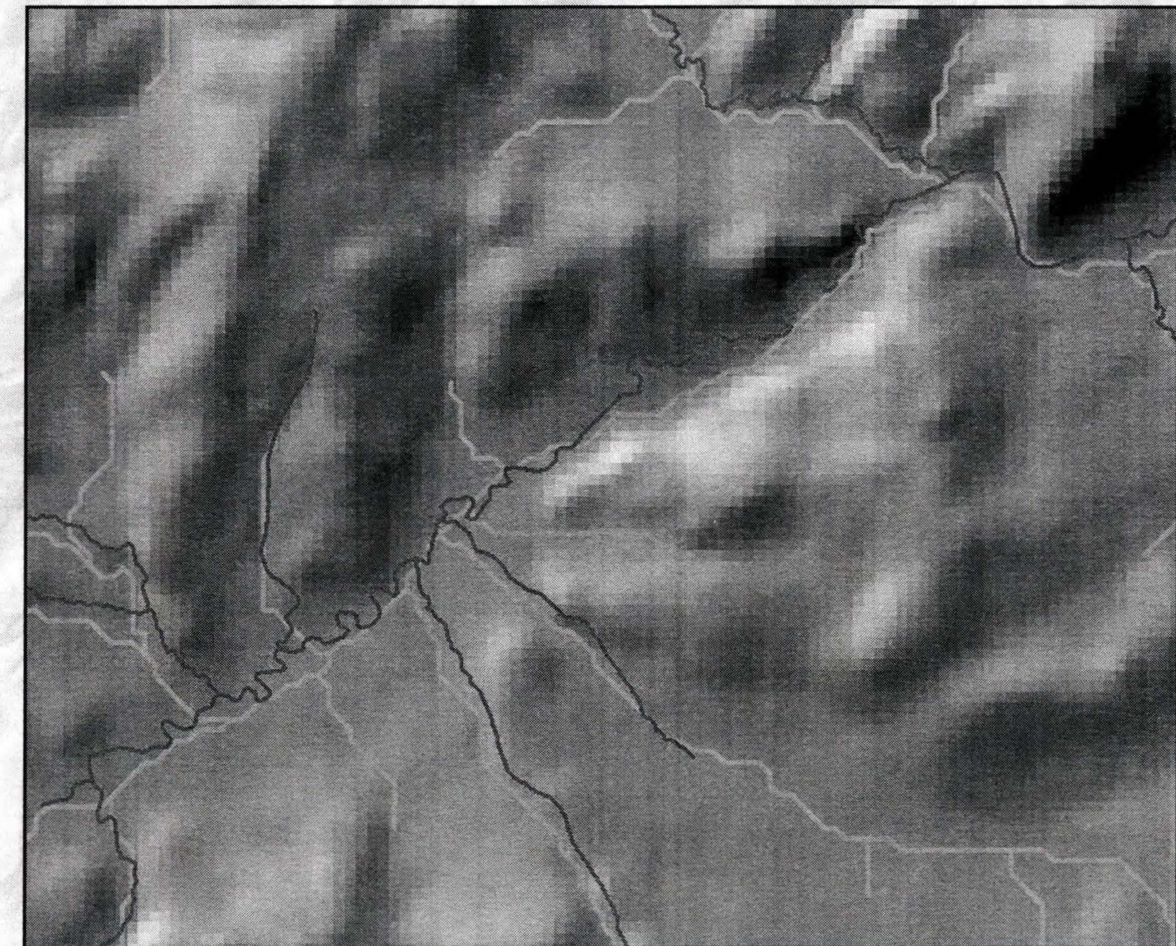


NHD and 10 m DEM Contours

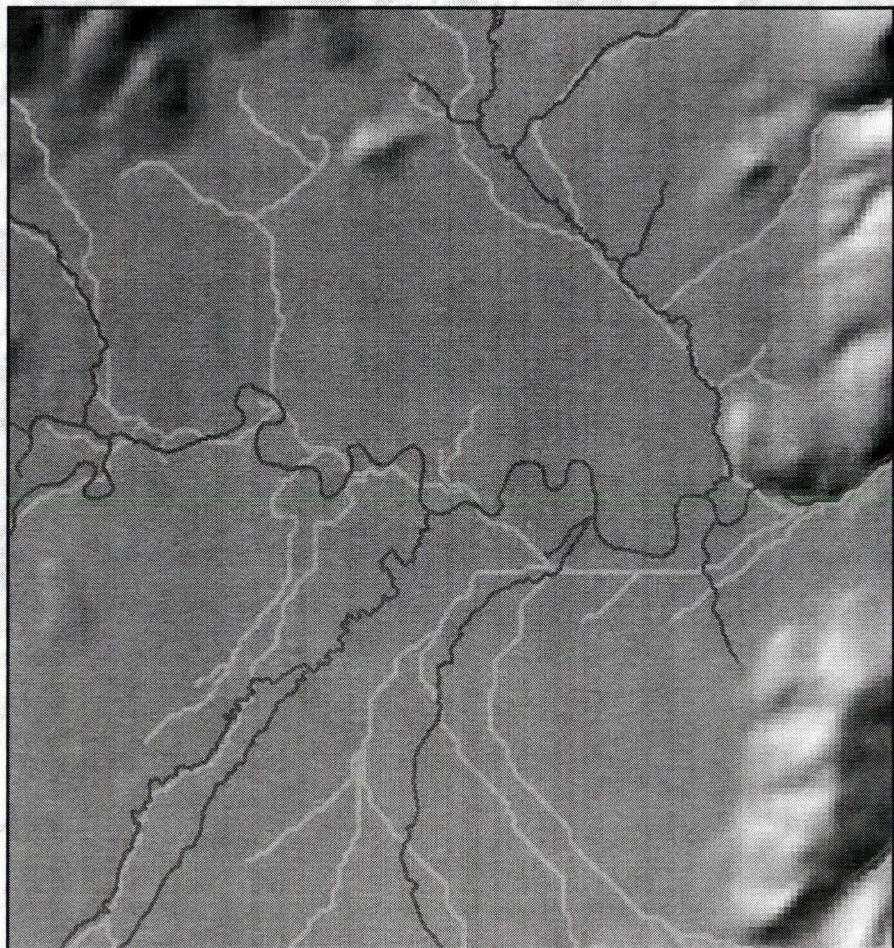
2 m interval



NHD Streams Represent Sinuosity More Accurately



Shortening with Synthetic Streams is Substantial



In low gradient areas, synthetic streams can underestimate stream length by approximately 25%

5412 m vs. 4092 m

The Dilemma

Elevations along synthetic streams consistently flow down hill and represent elevation (rise) more normally

However….

Stream channel length, or sinuosity (run) is better represented by NHD stream lines

Rise / Run = Slope

Best Data Choices for Computing Stream Channel Gradient

1) 10 m NED DEM

2) NHD stream lines

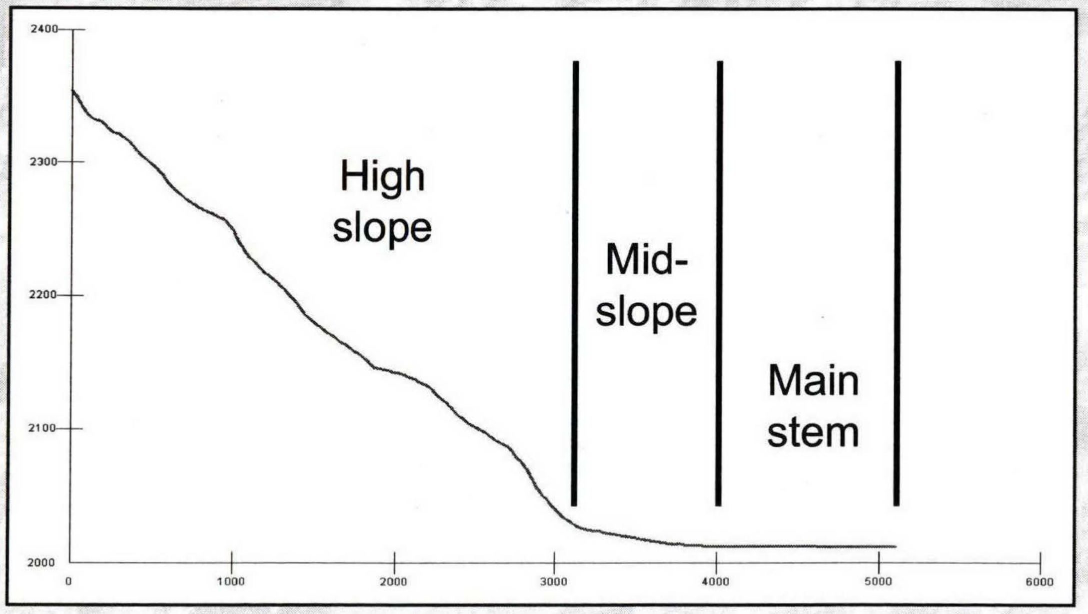
Spatial Accuracy of NHD

Measuring Gradient

Measuring Gradient

We used three approaches dependent on gradient

1) High slope – 3% - 50% gradient
2) Mid-slope – 1.4% mean
3) Main stem – 1.0% or less



Stream channel profile

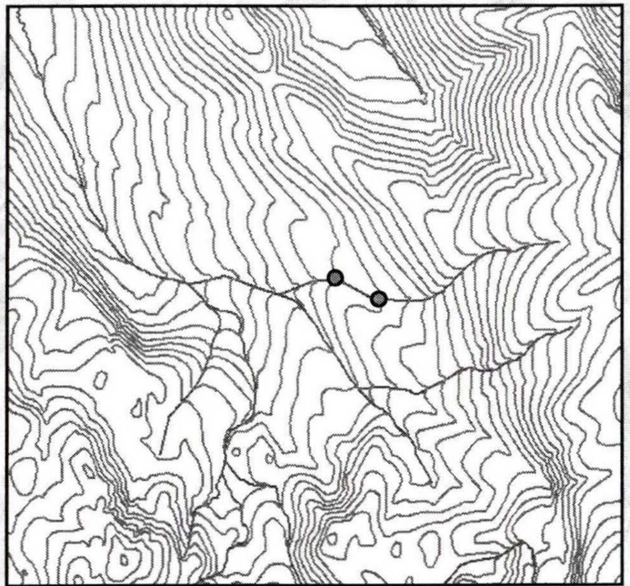
Why Use Three Approaches?

DEM accuracy changes depending on the original quad contour spacing

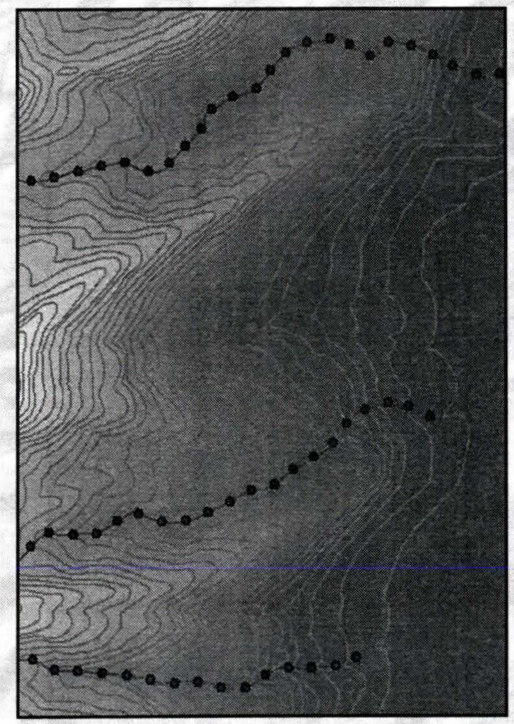
and

Landscape position

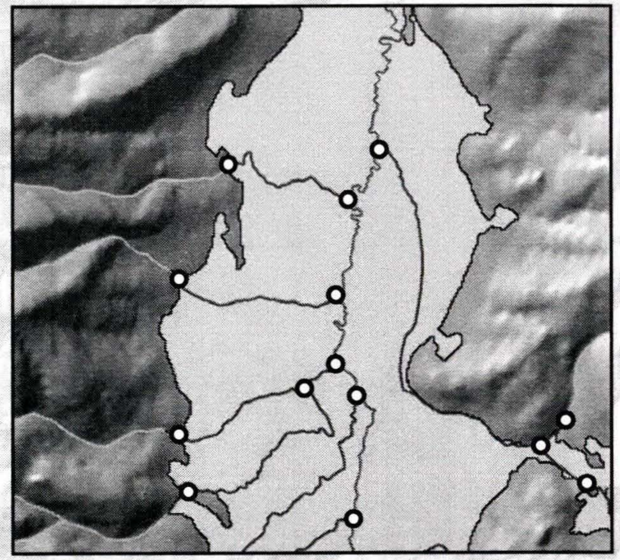
Possible Approaches



At contour crossings



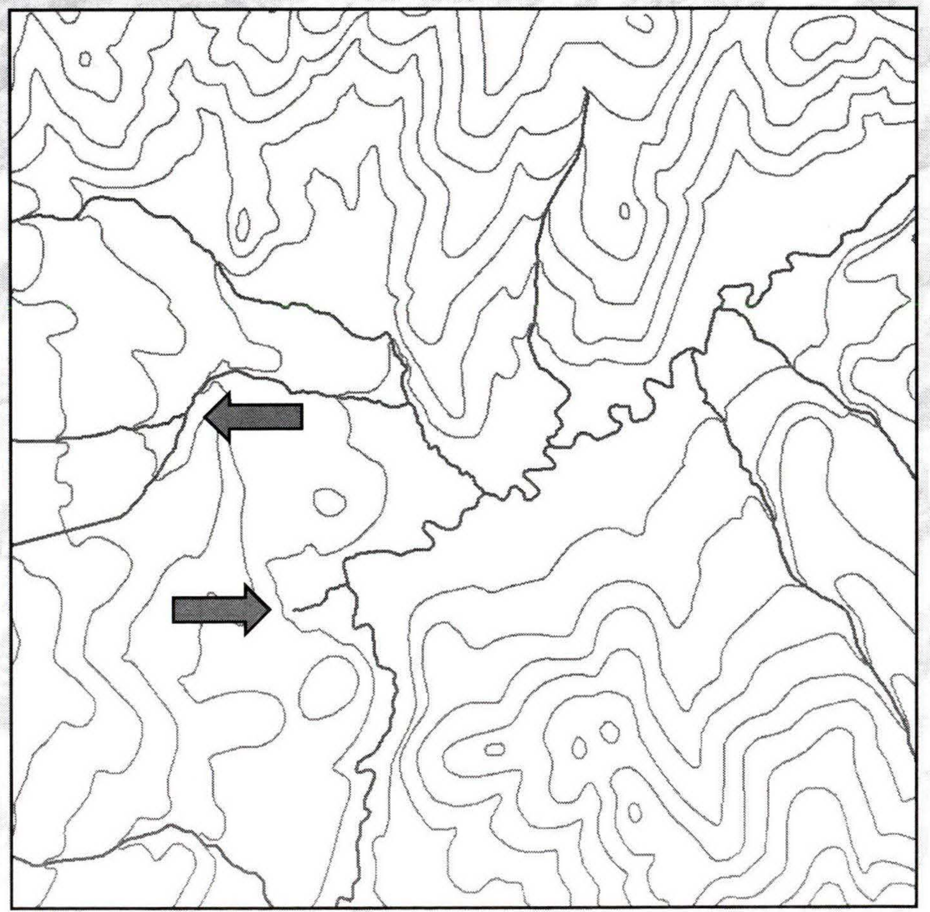
Equal interval



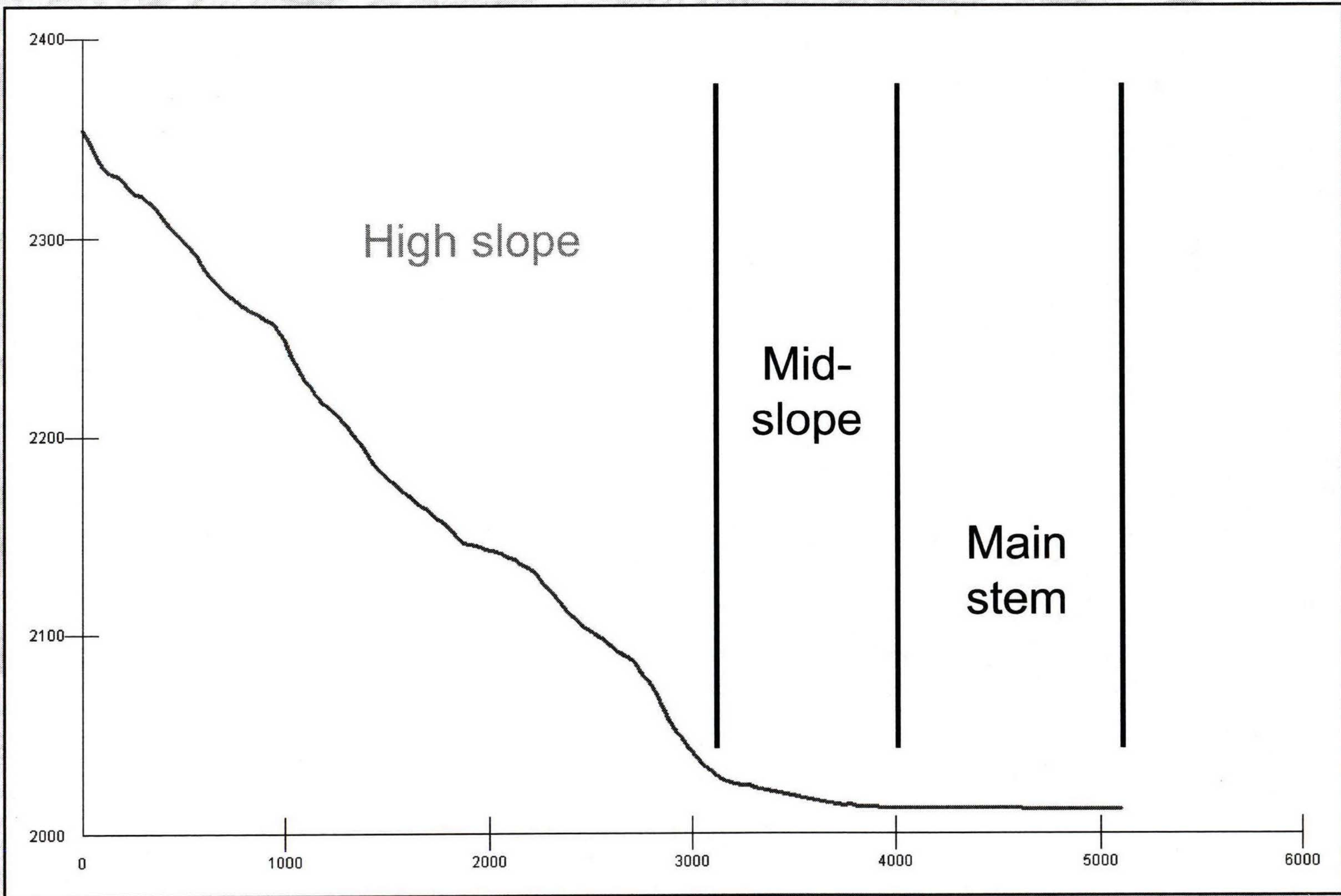
At stream intersections

Why Not Use Contour Crossings for Entire Study Area?

1) Not available for the entire study area
2) Tag ends and stream intersections create technical problems

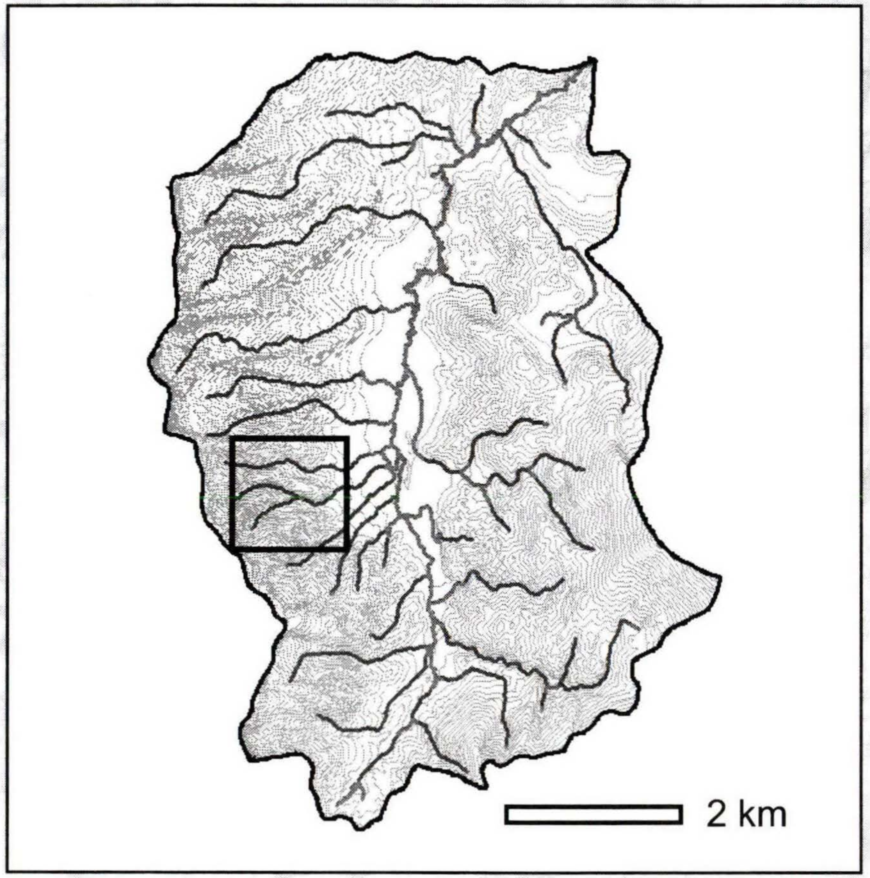


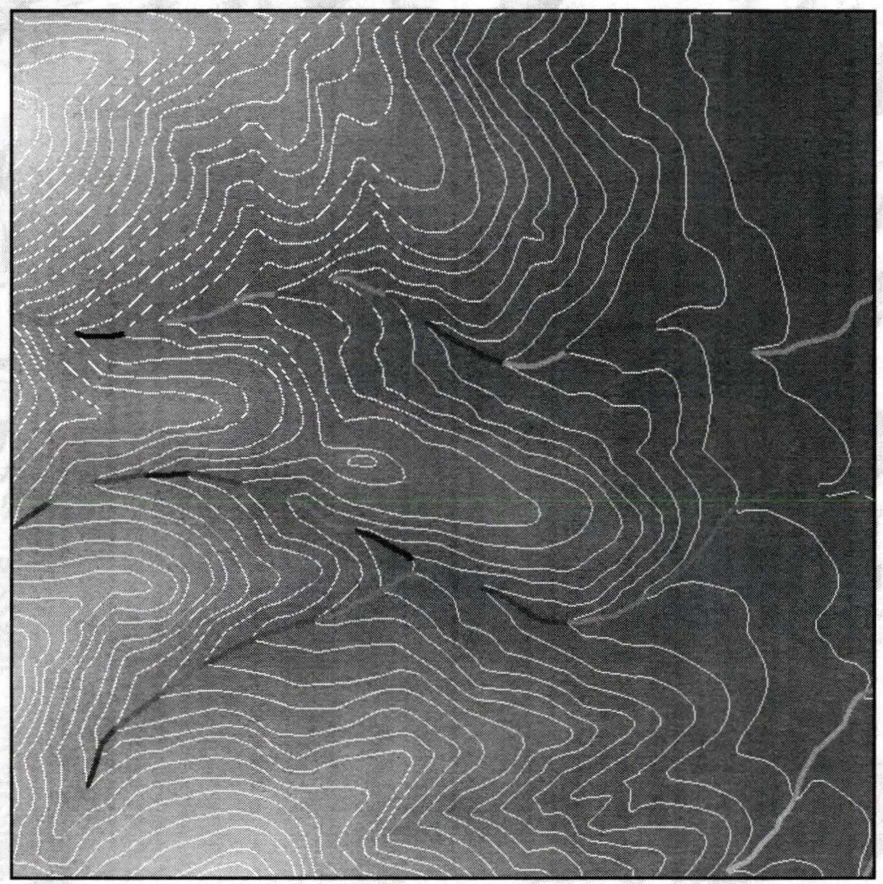
High Slope



We'll use 100 m equal intervals

10 m DEM Accuracy in Higher Gradient Areas

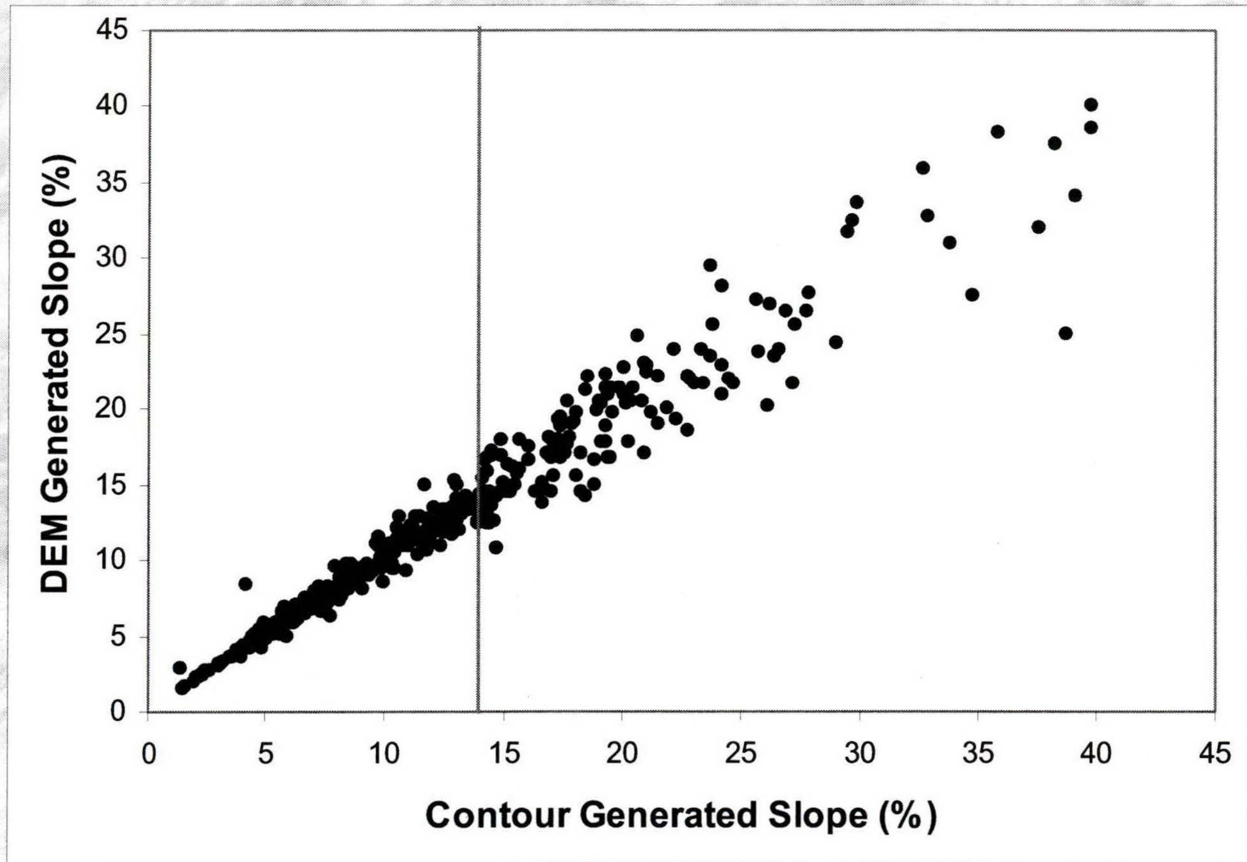




Blue = higher gradient streams

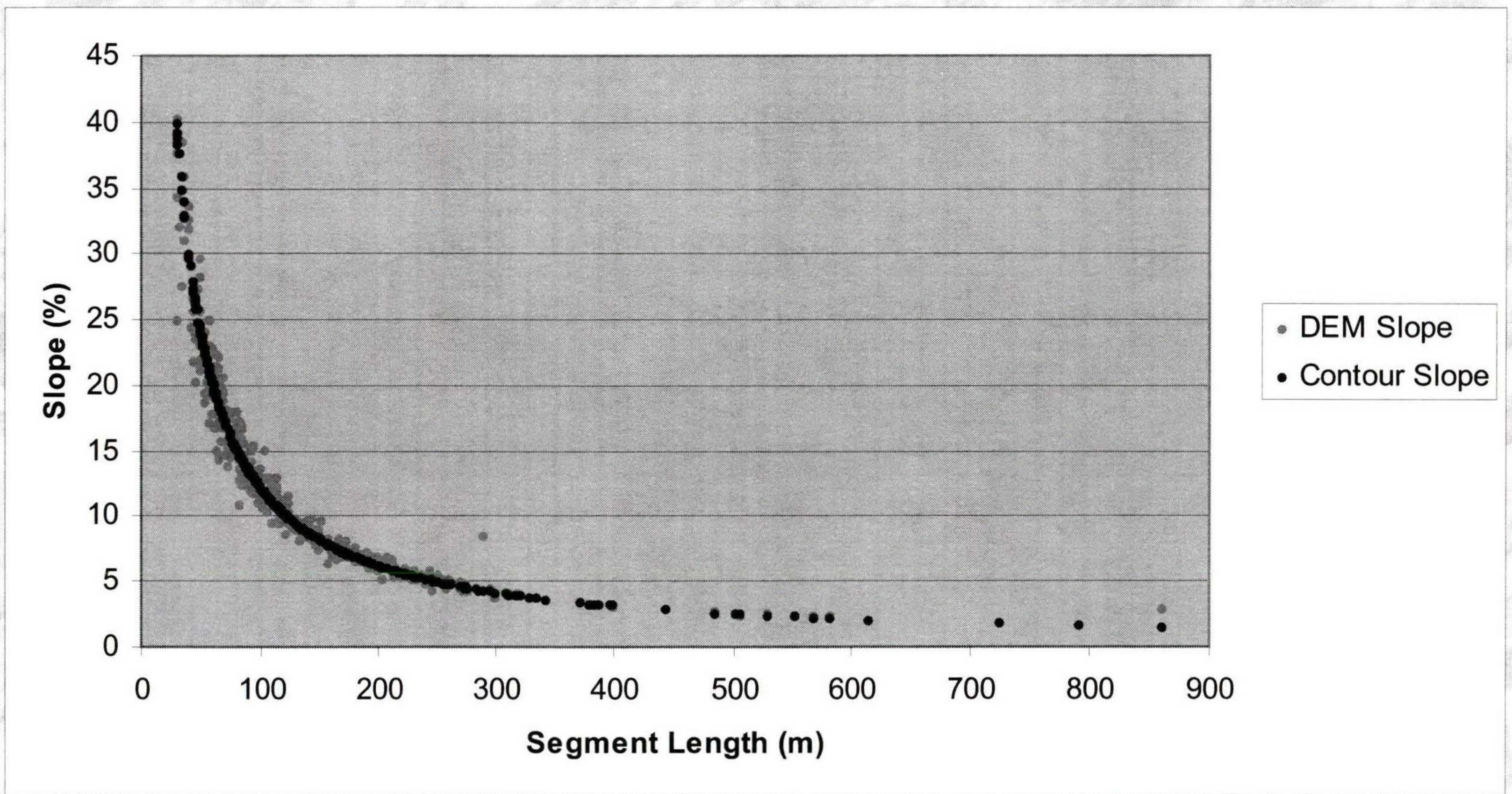
For comparison, compute slope using 1:24 k contours and DEM

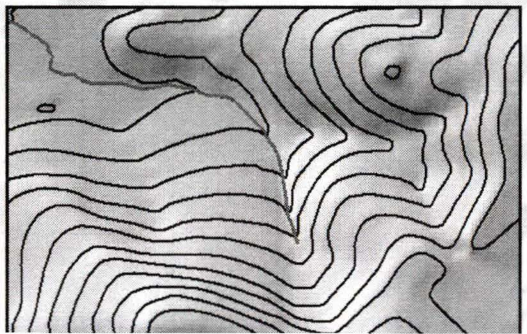
Contour and DEM Generated Slope Comparison



Note divergence at higher slopes

Slope and Segment Length

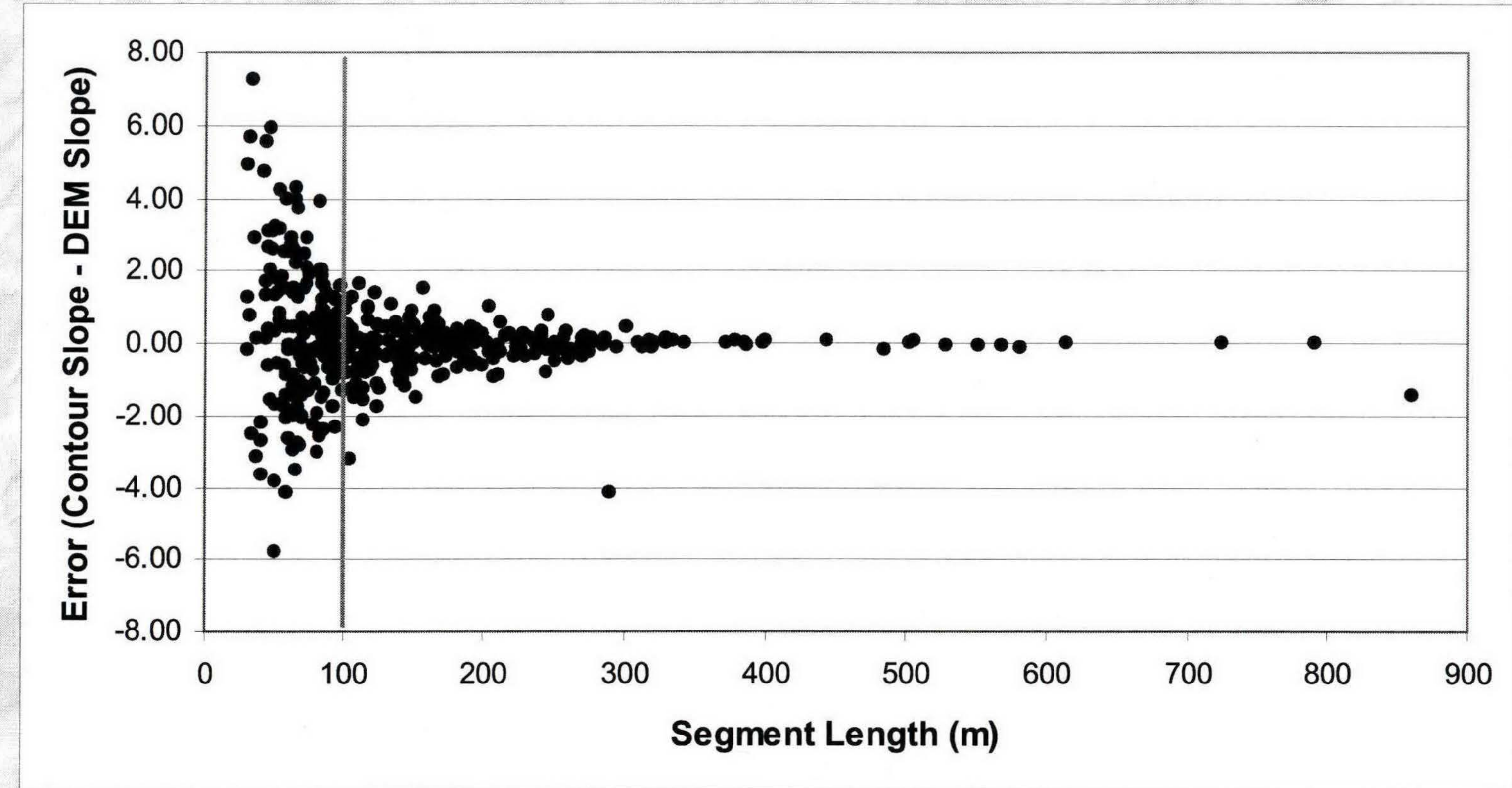


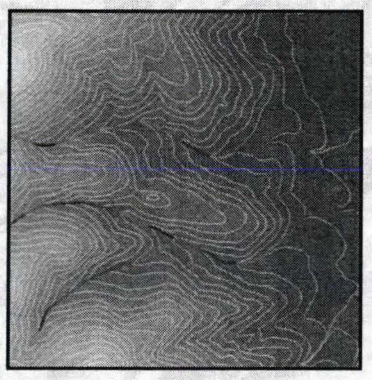


Contours get closer together at higher slopes and segment length decreases

Note error in DEM model

Errors vs. Stream Segment Length



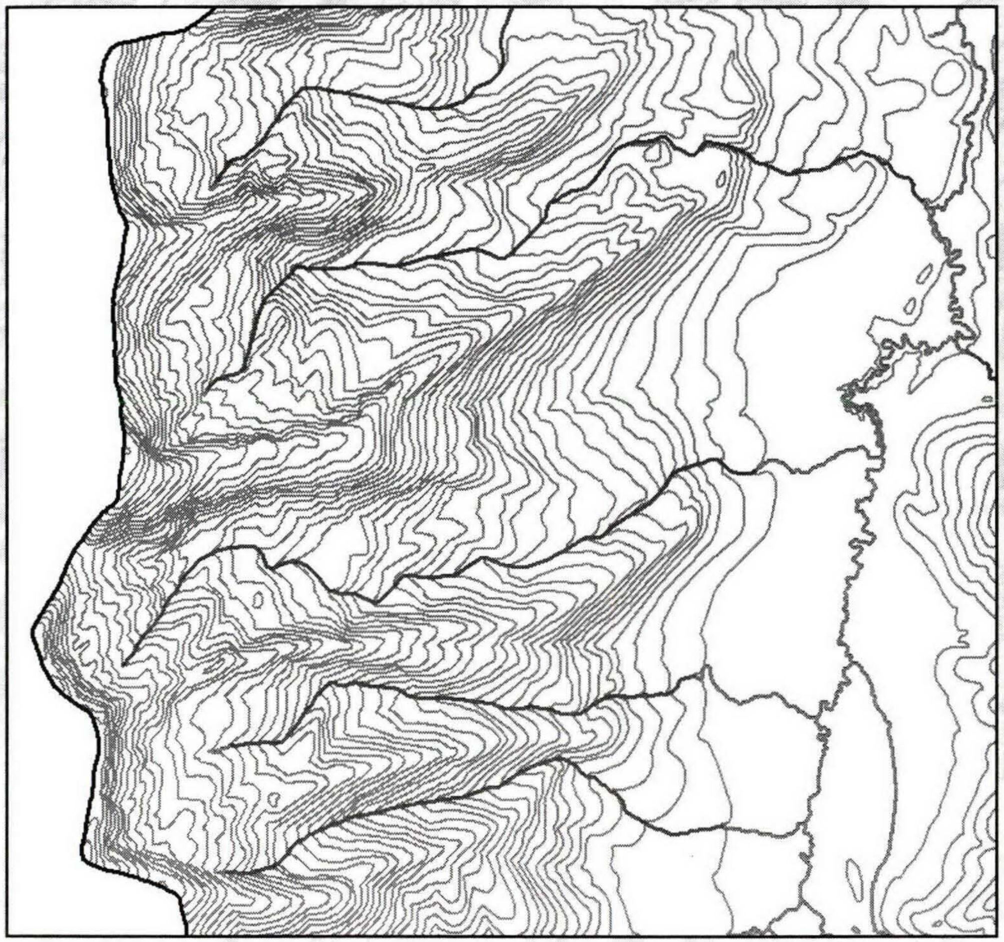


Mean slope error for segment lengths:

Greater than 100 m	.42% pts
Equal to 100 m	.68% pts
Less than 100 m	1.64% pts

Median Stream Segment Length

40' Contour Interval

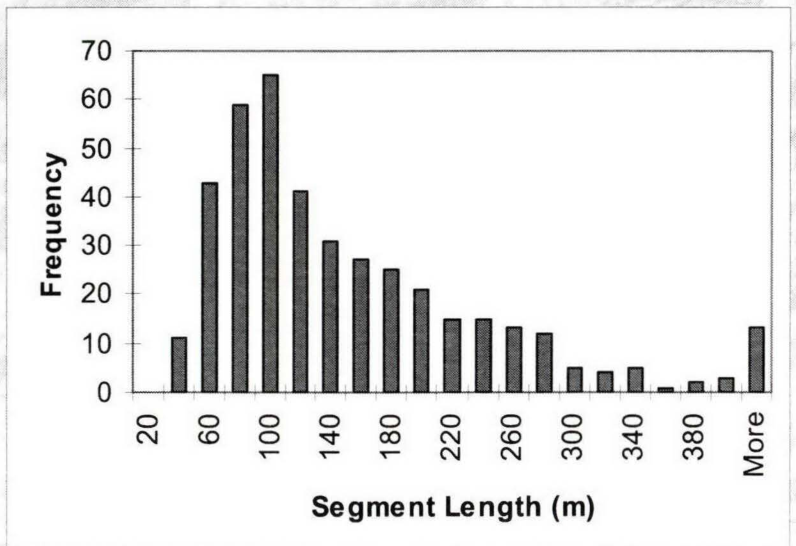


Segment length between contours

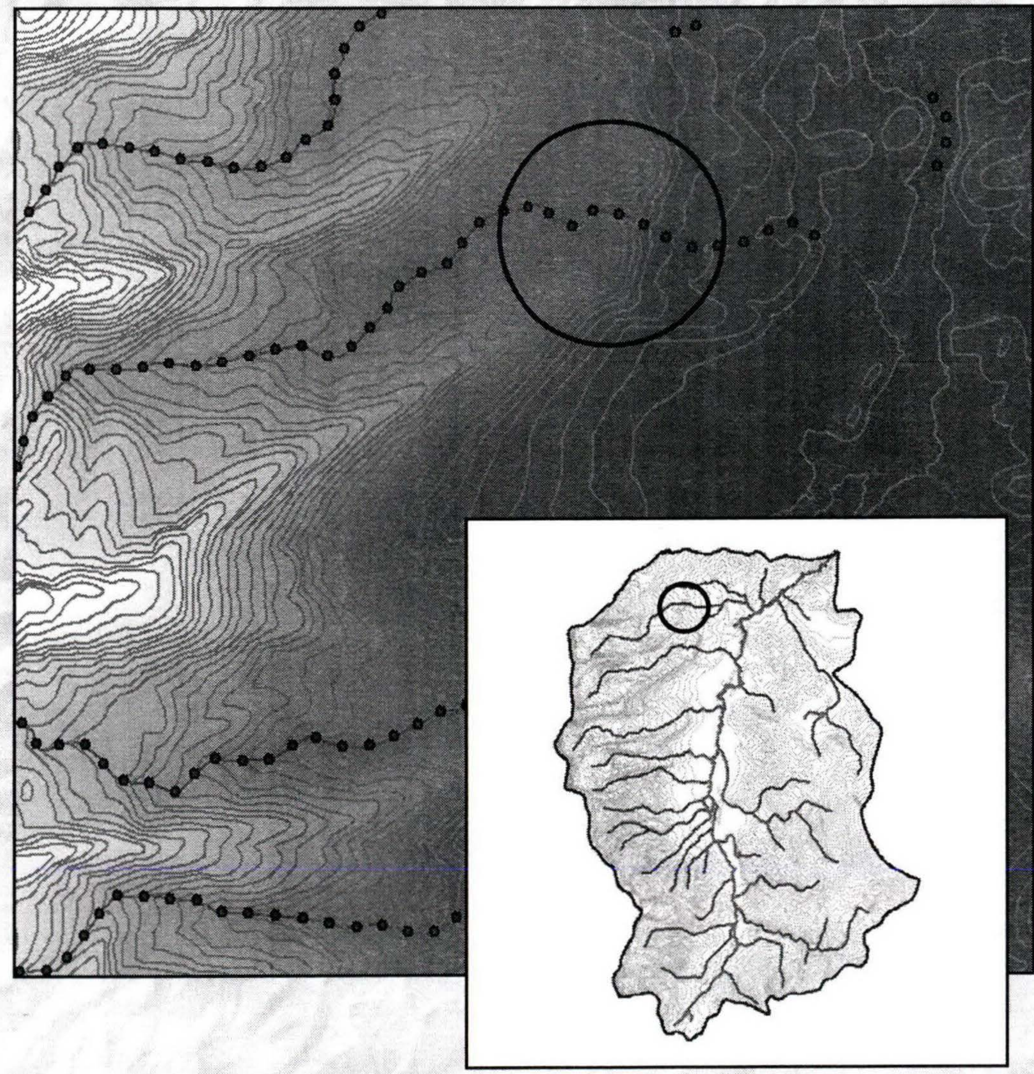
Mean = 147 m

Median = 114 m

n = 411



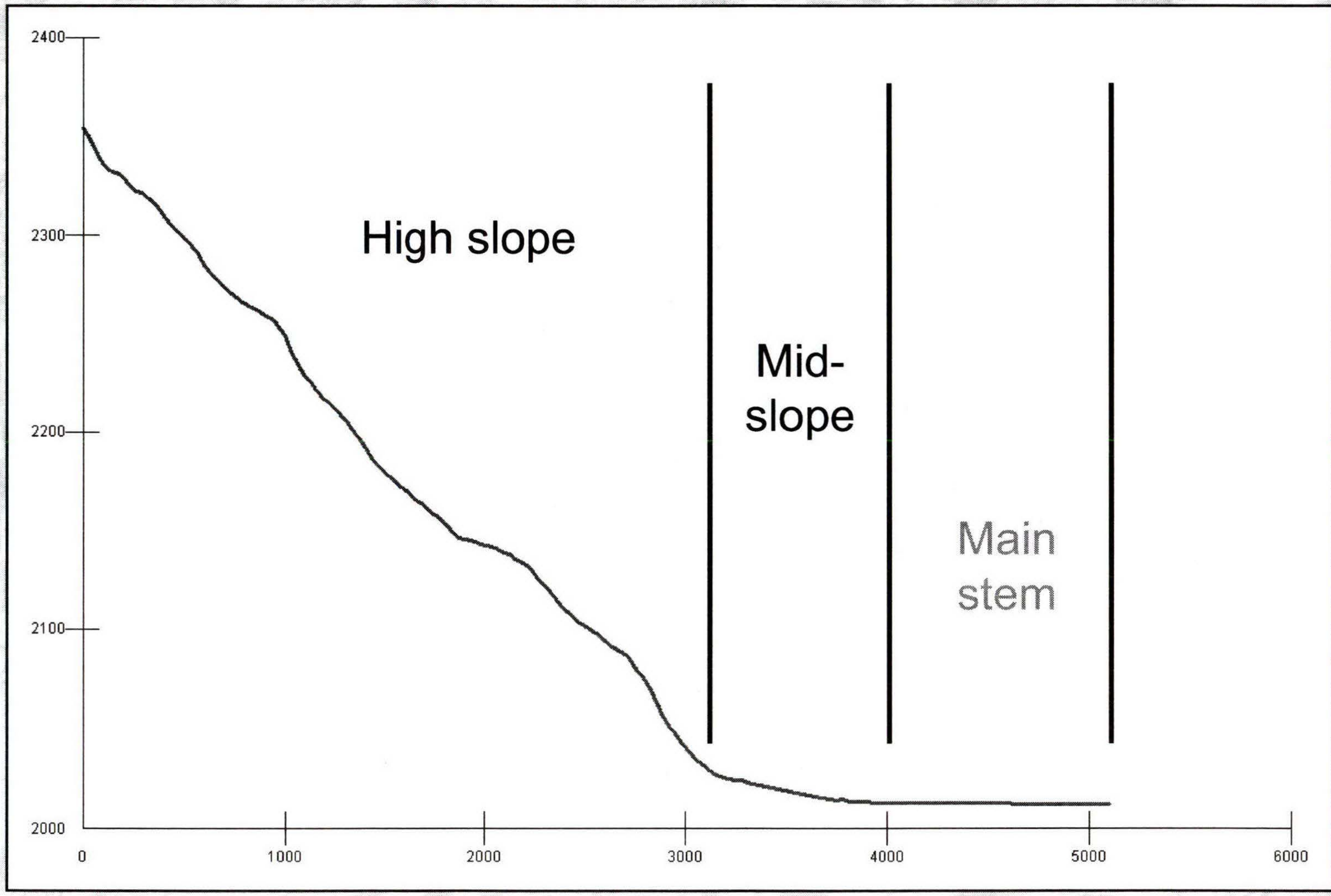
Gradient Calculation for Higher Slope Reaches – 100 m Spacing



1) We used 100 m interval spacing along NHD lines with 10 m DEM.
2) Fine enough resolution to detect some natural barriers (slope > 20%)
3) Not so coarse that undesirable averaging occurs

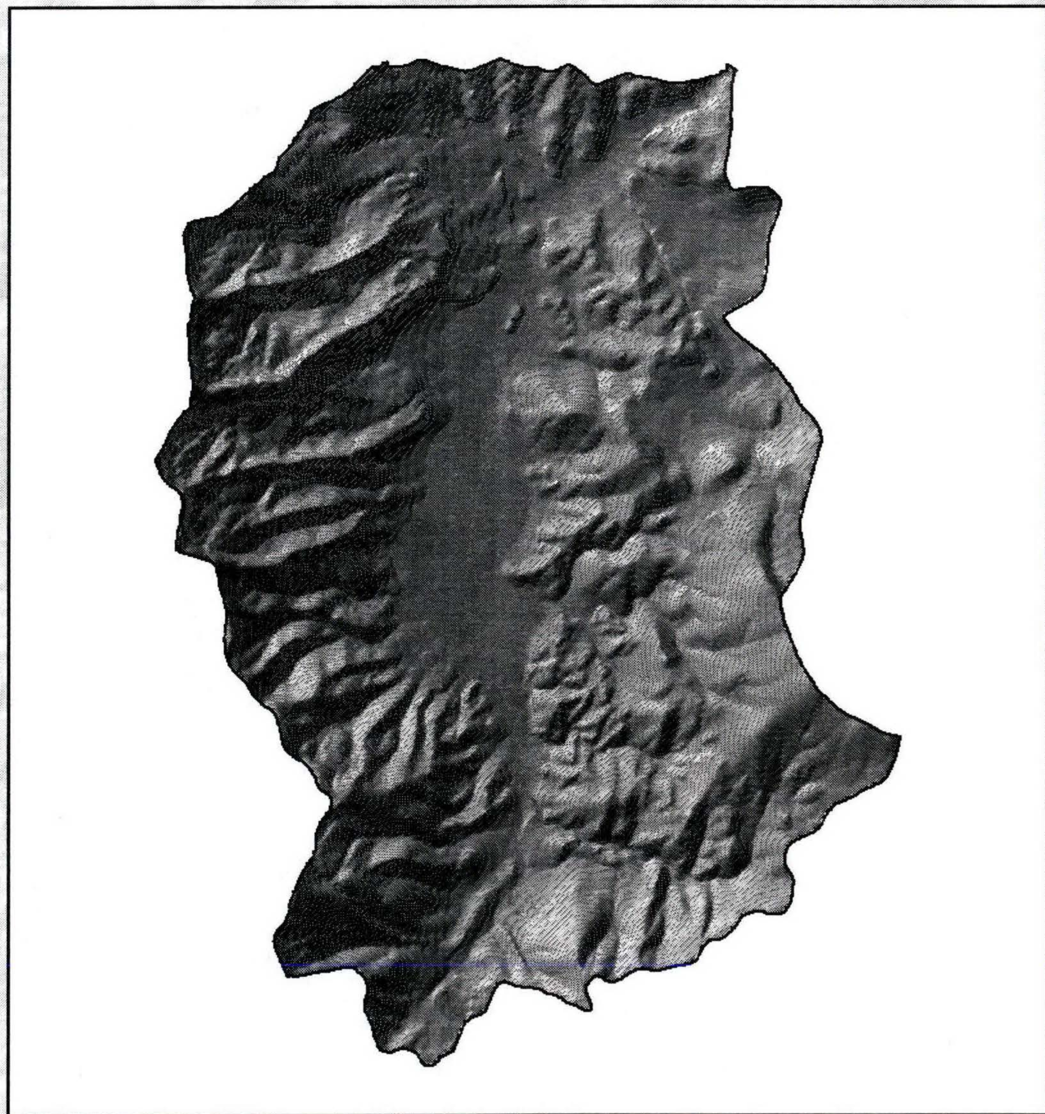
Average error = 0.68% pts

Main Stem

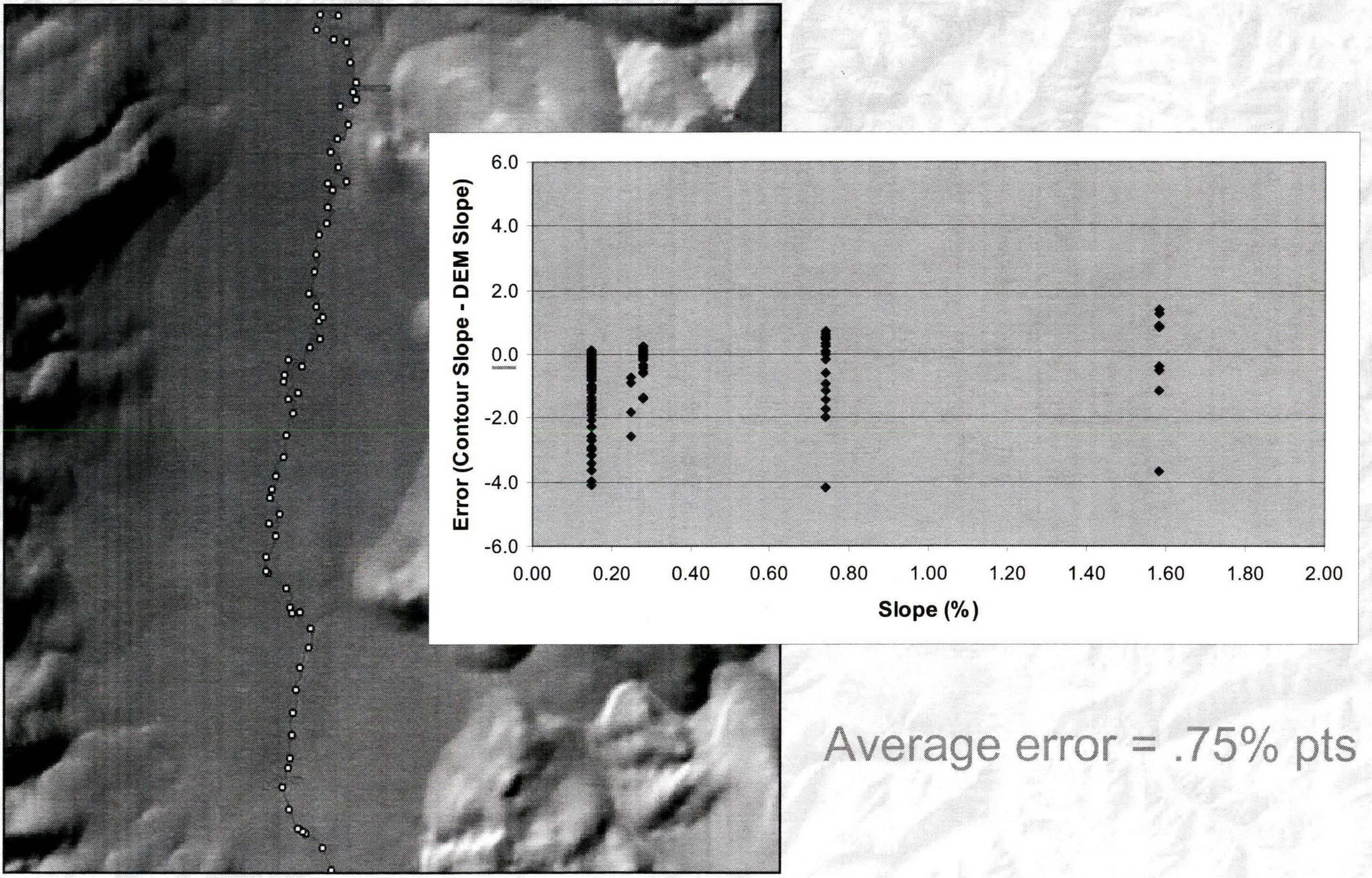


2400
2300
2200
2100
2000
0
1000
2000
3000
4000
5000
6000
High slope
Mid-slope
Main stem

Gradient Calculation for Main Stem Reaches

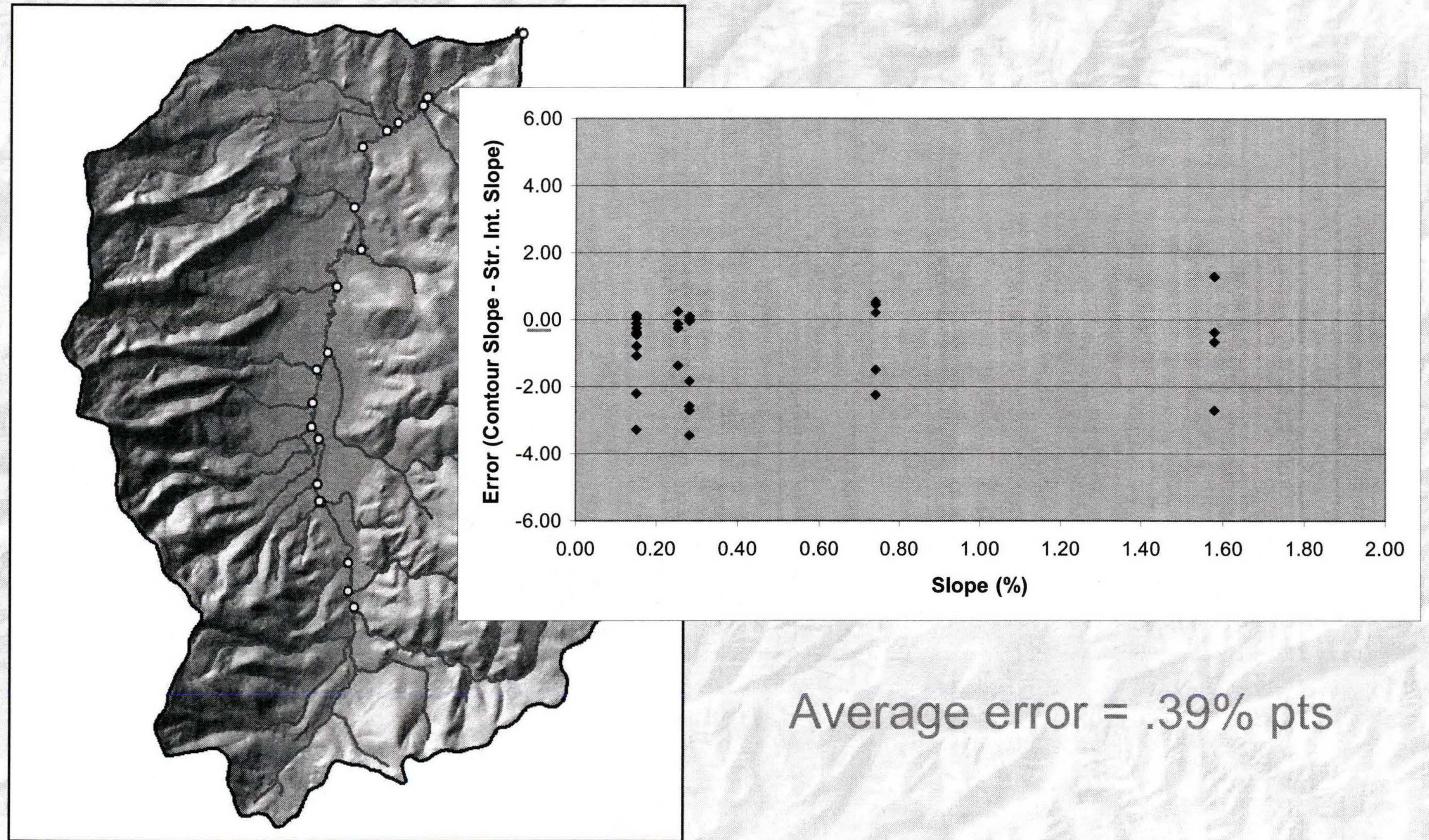


Contour Slope vs. 100 m Interval



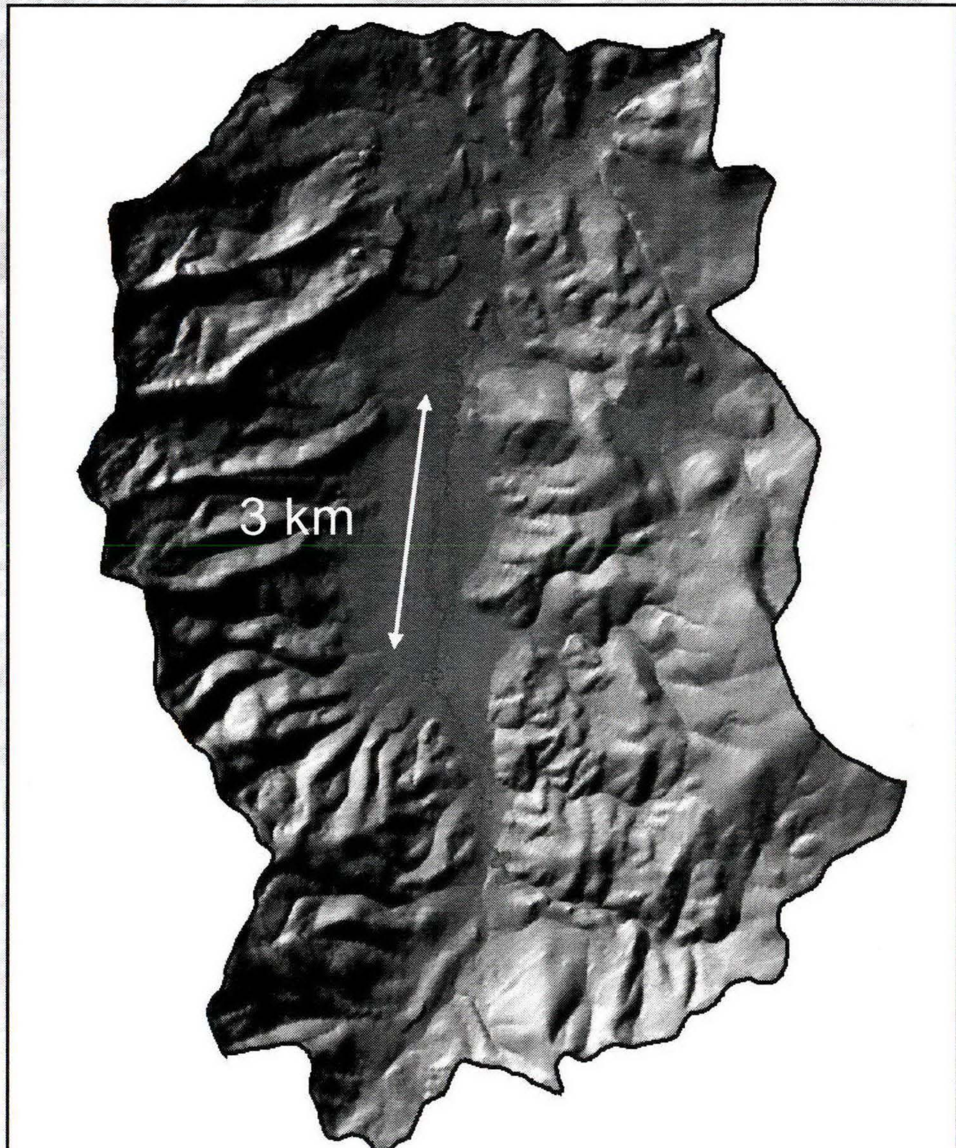
Average error = .75% pts

Gradient Calculation for Main Stem Reaches
Stream Intersections

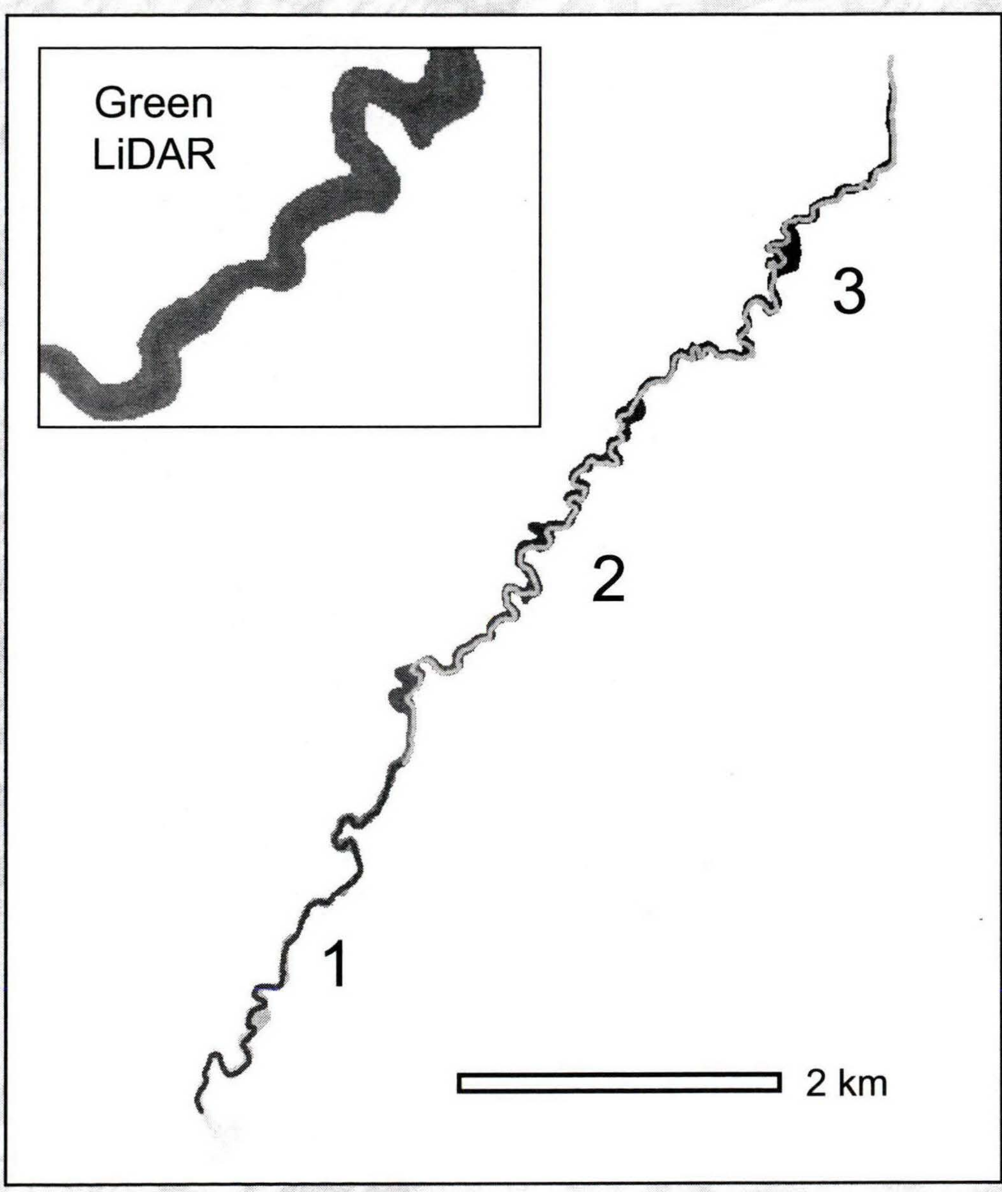


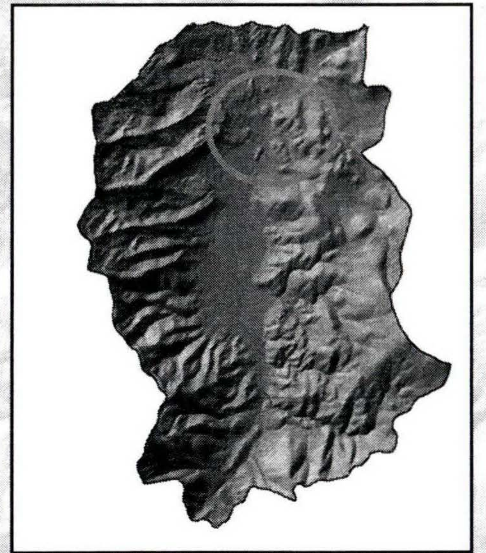
Average error = .39% pts

Gradient Calculation for Main Stem Reaches at Contour Crossings



LiDAR vs. Contour Gradient Comparison

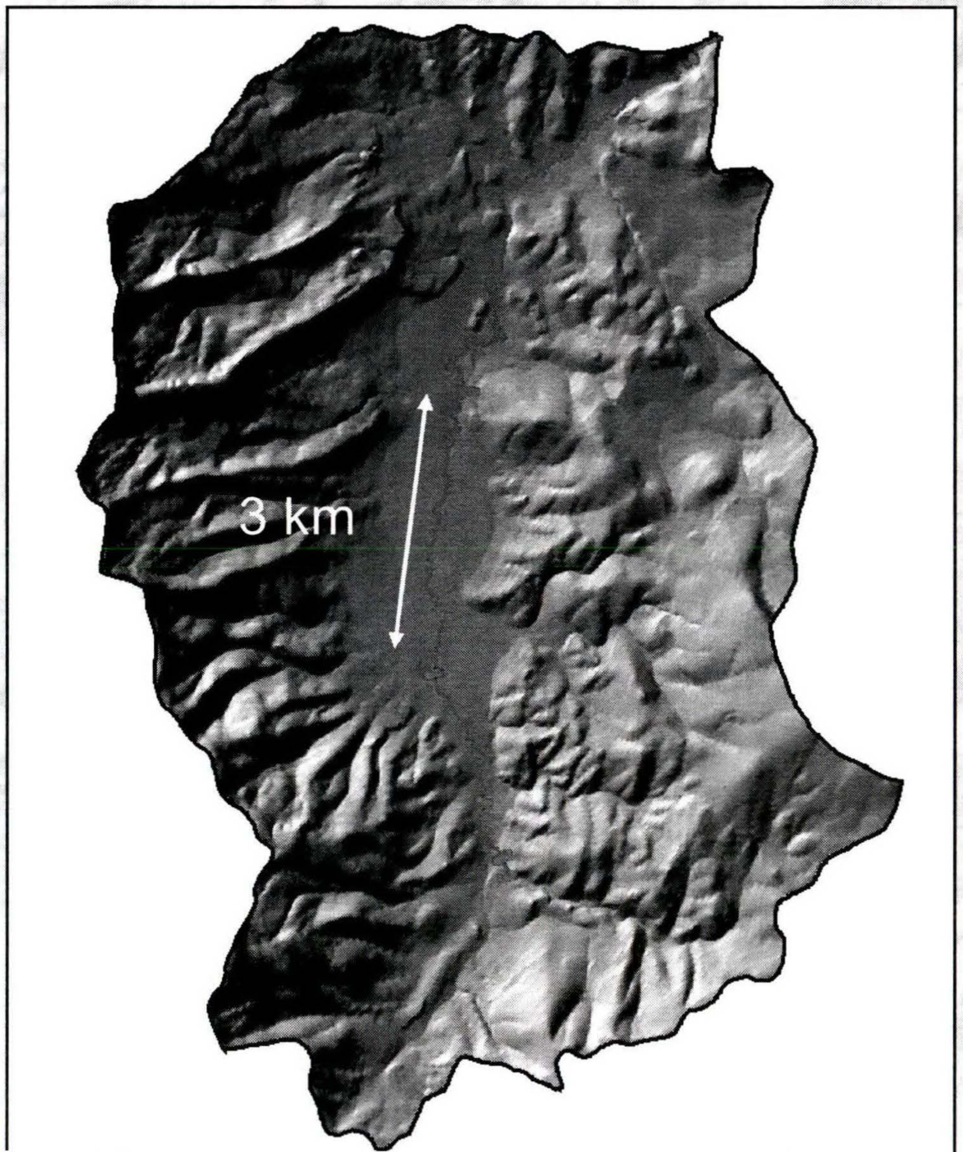




Segment No.	Contour Slope	LiDAR Slope
1	.41%	.45%
2	.35%	.35%
3	.36%	.32%

Average error = .03% pts

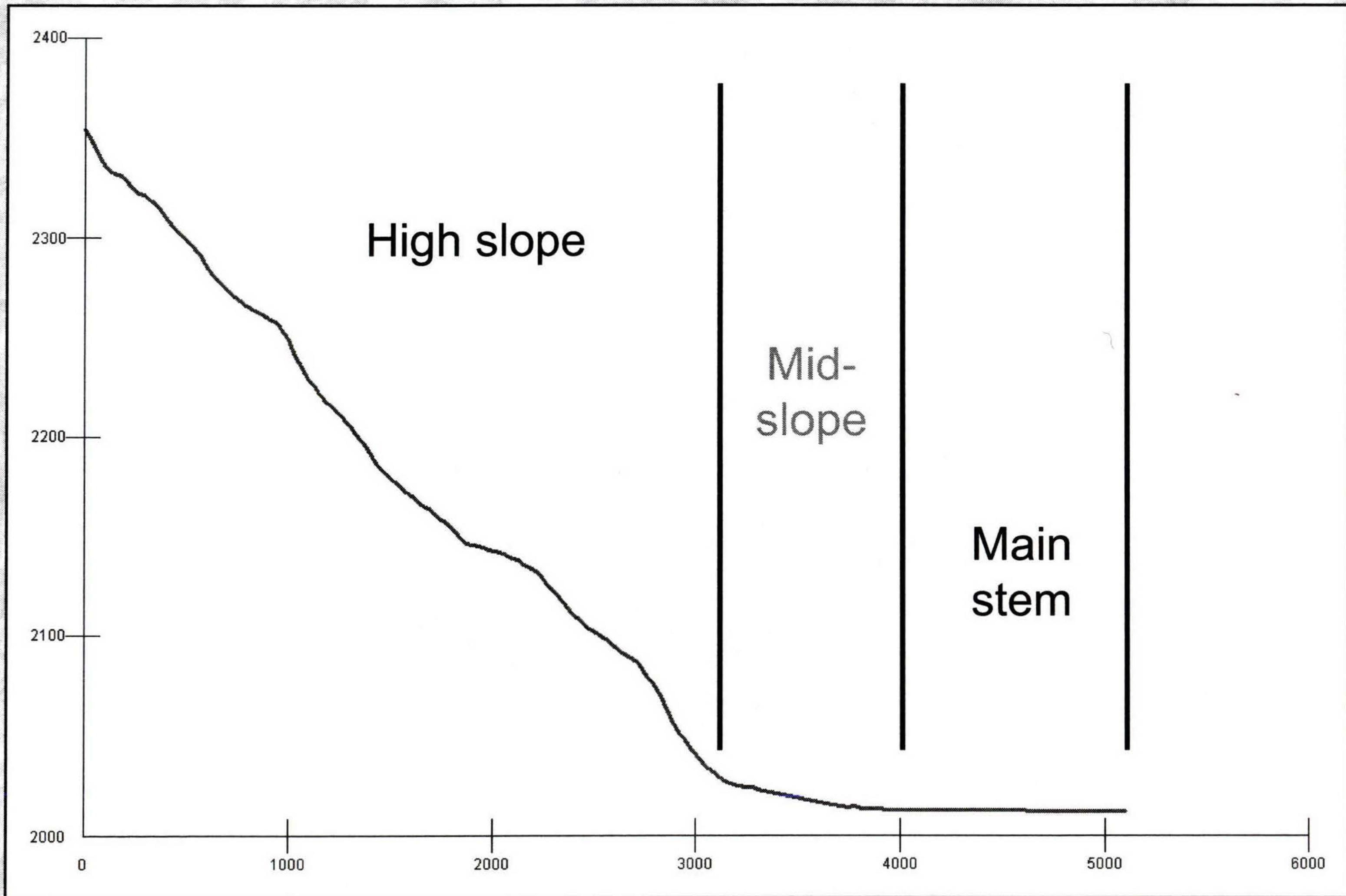
Gradient Calculation for Main Stem Reaches



- We used quad contour crossings along main stem
- Contour crossings were digitized on-screen from DRGs

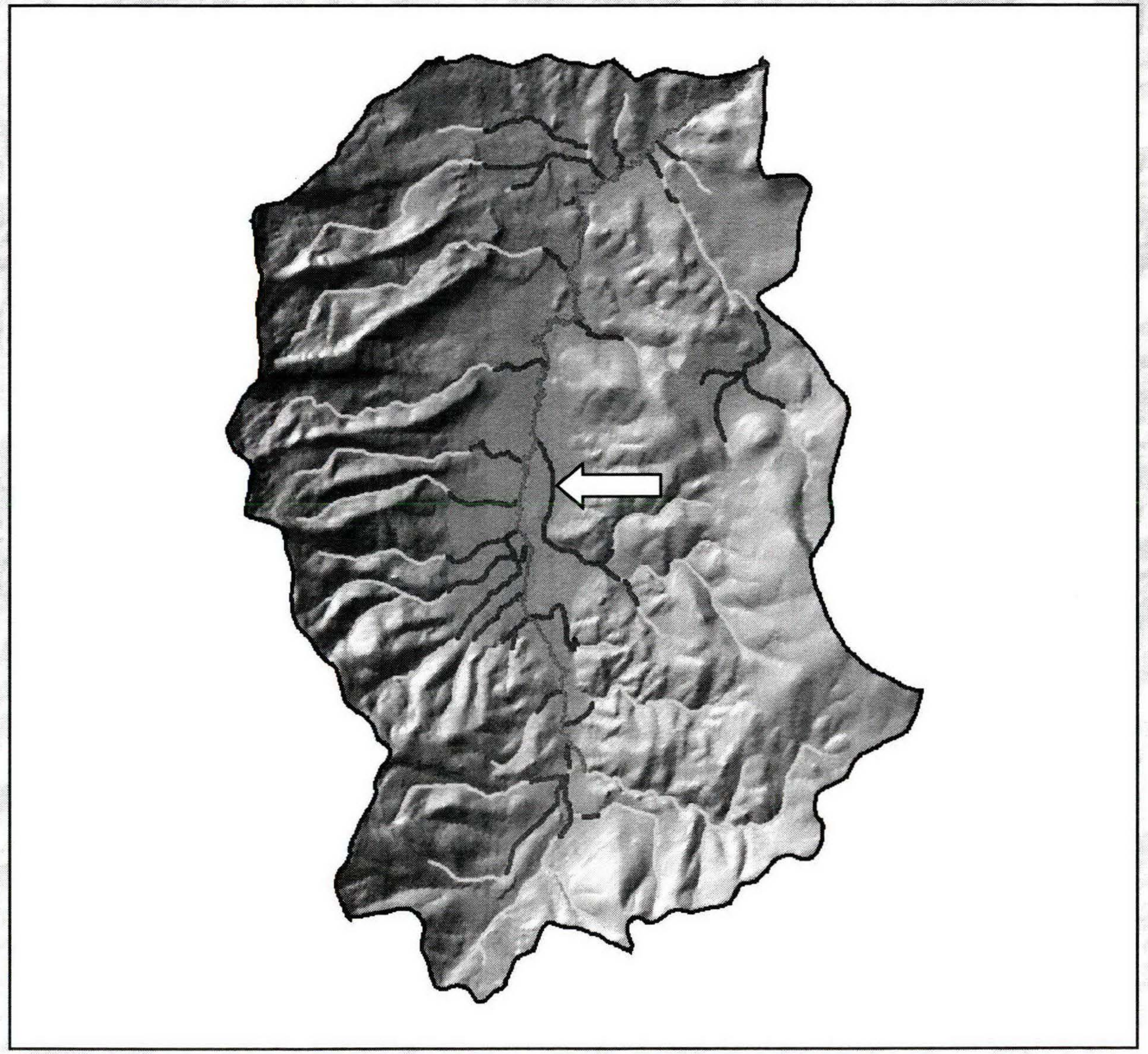
Average error = .03% pts

Mid-slope

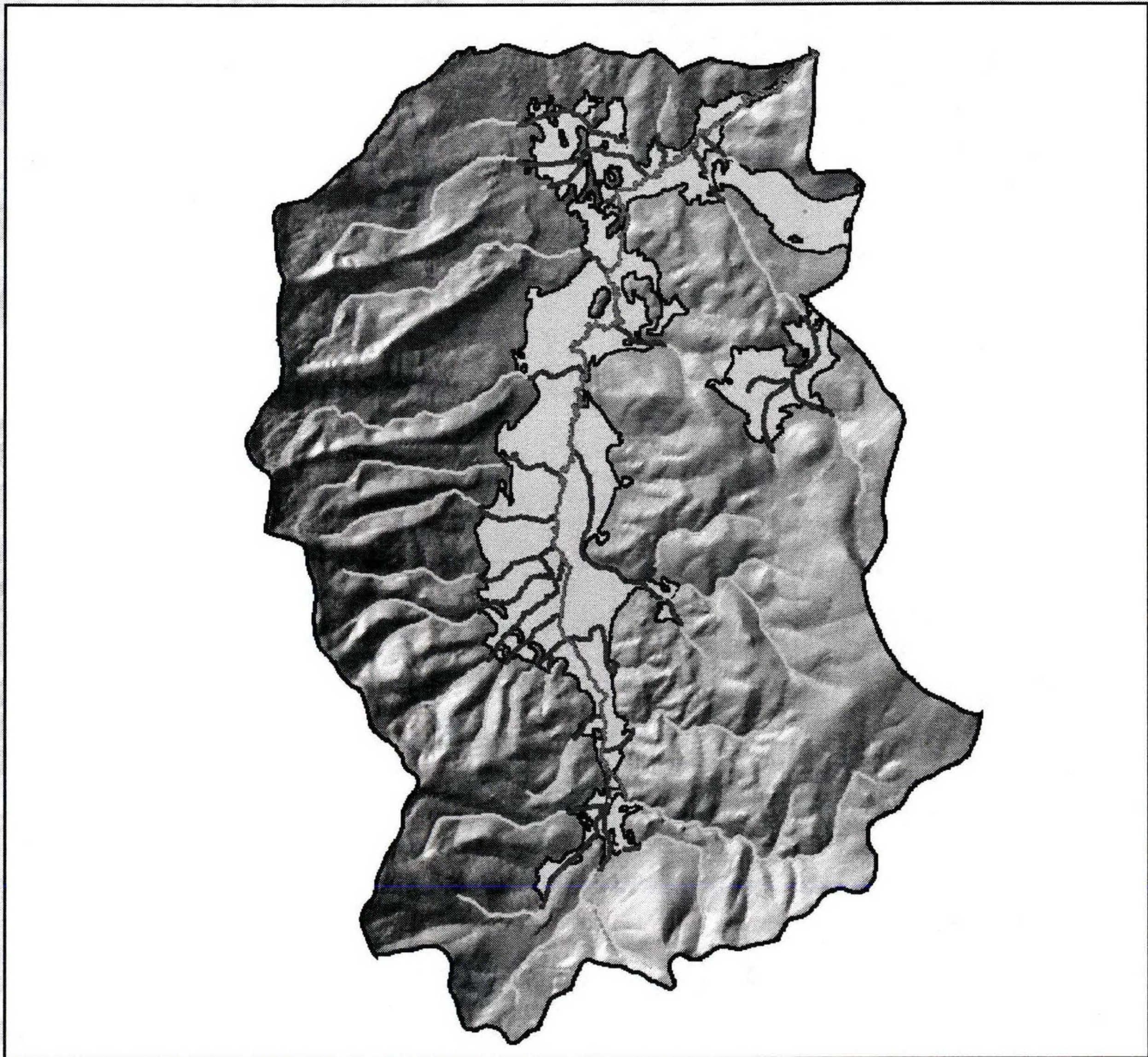


2400
2300
2200
2100
2000
0
1000
2000
3000
4000
5000
6000
High slope
Mid-
slope
Main
stem

Mid-slope Reaches



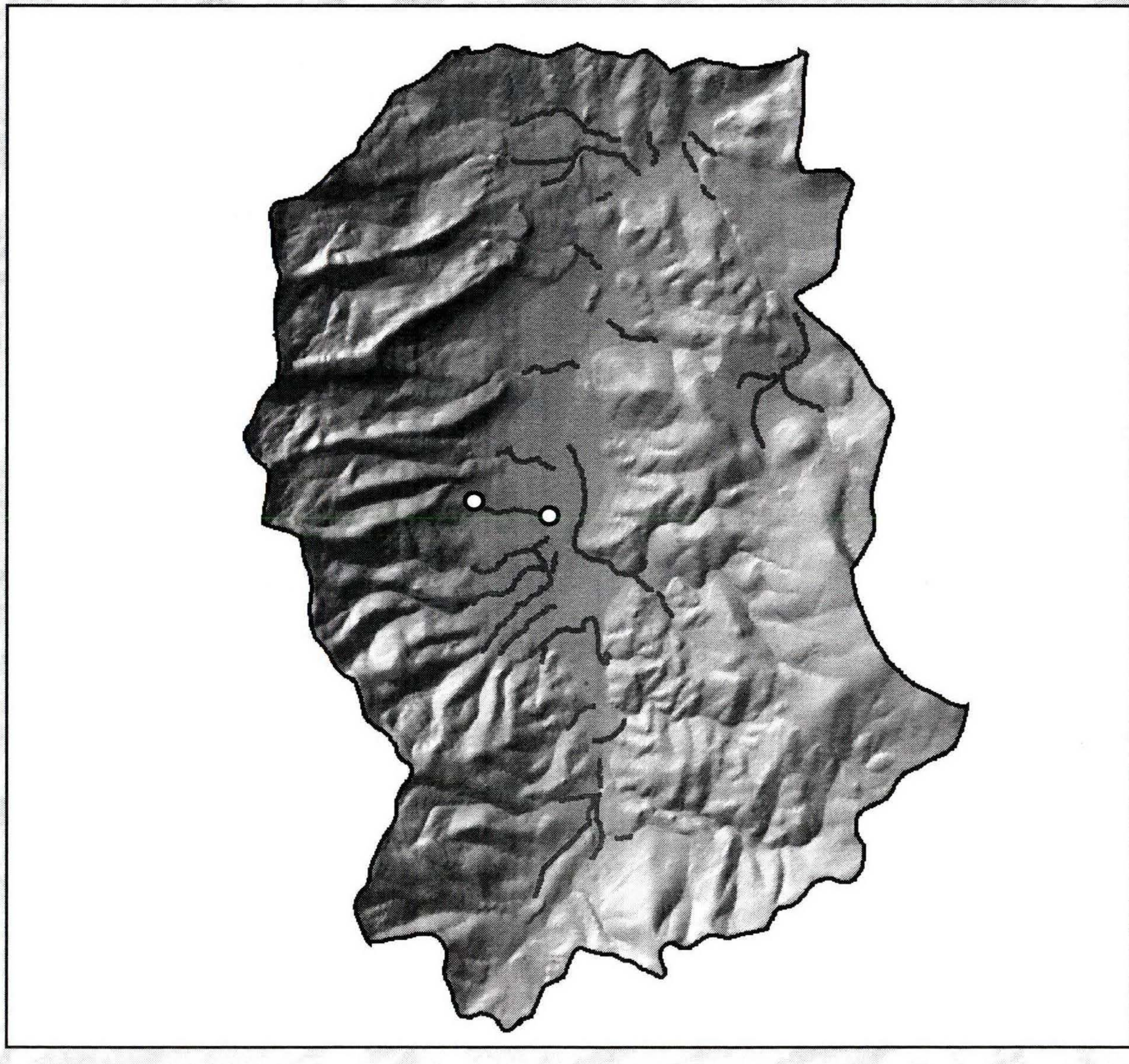
Mid-slope Reaches and Flat Valley Bottom Delineation



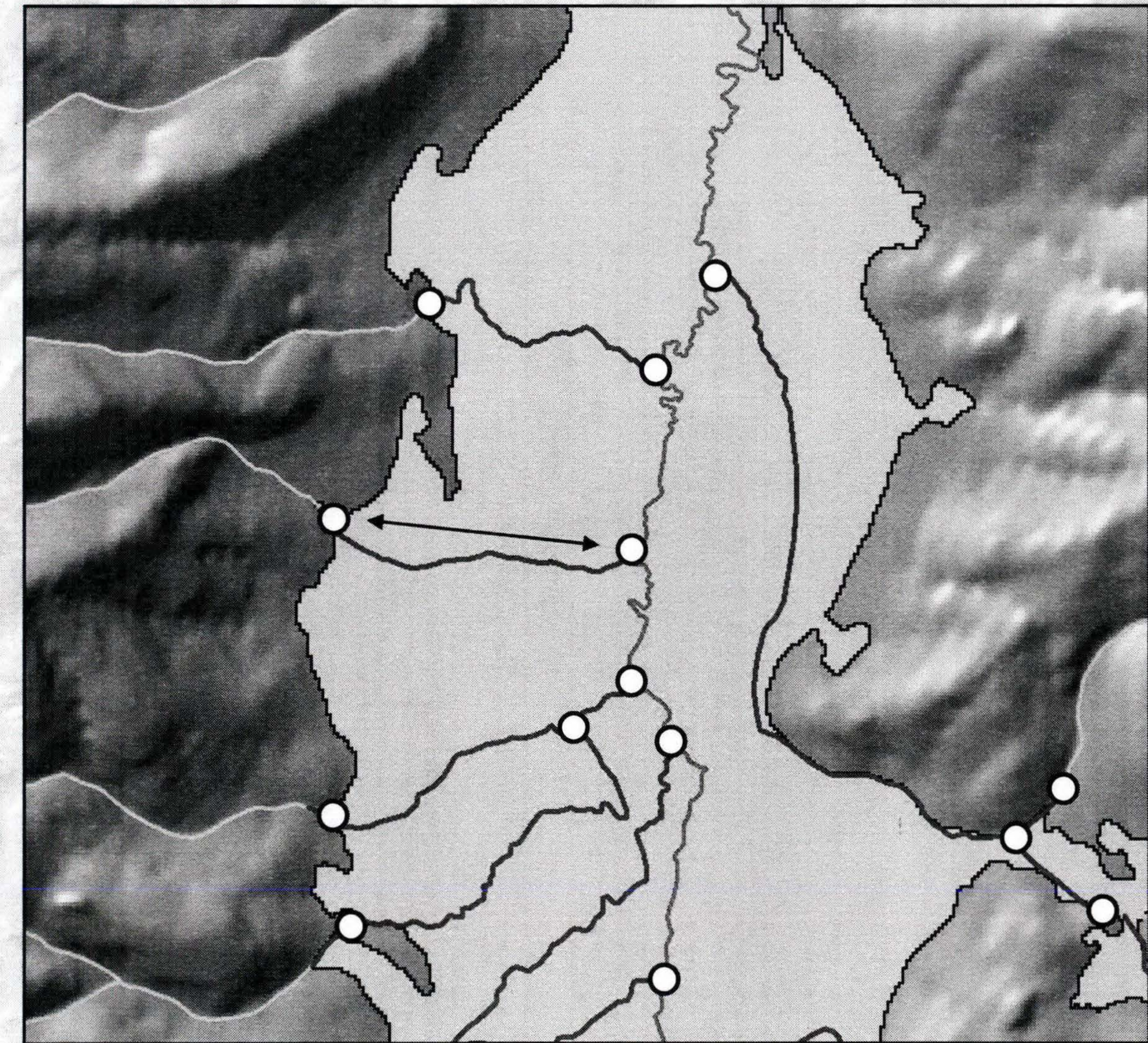
Procedure

1) Overlay valley bottom
2) Exclude main stem reaches

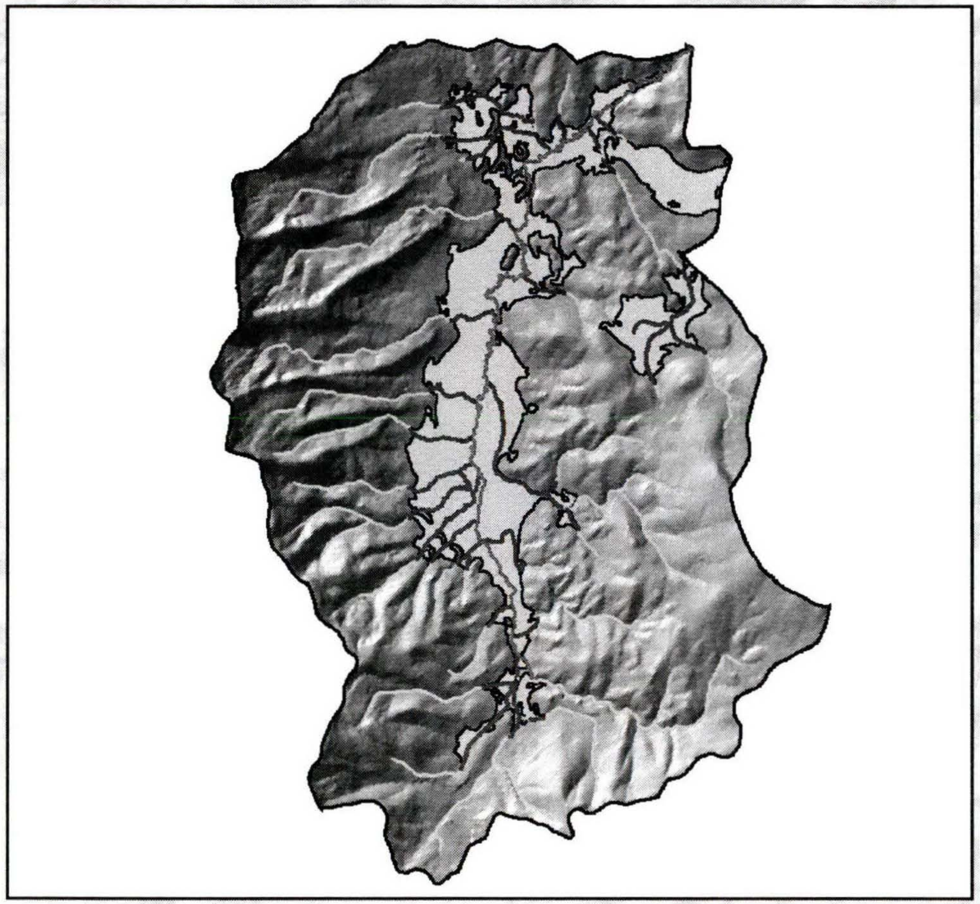
Mid-slope Reaches



Compute Slope Between Break Lines and Stream Intersections with 10 m DEM



Gradient Calculation for Mid-slope Reaches

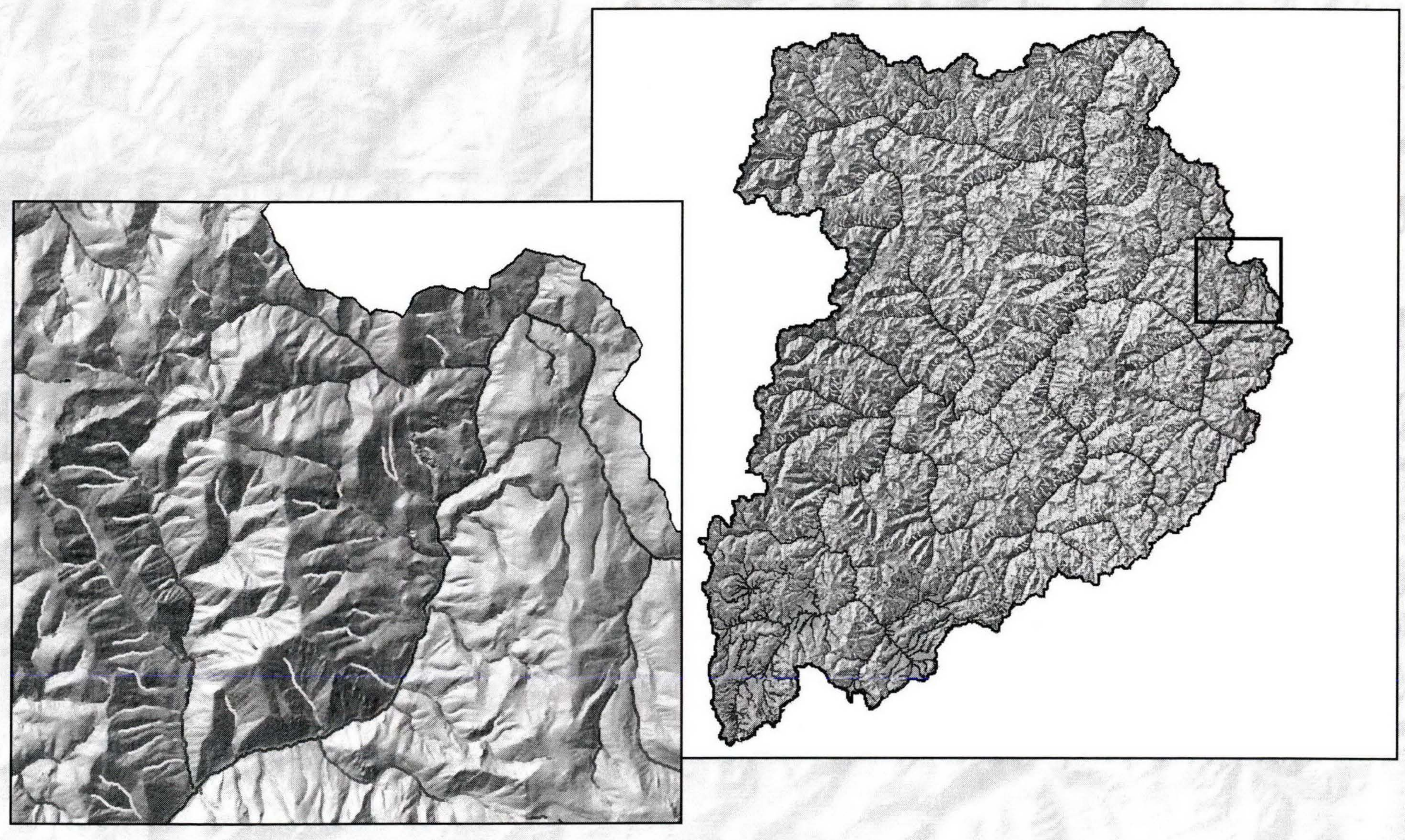


1) We used 10 m DEM elevations at valley bottom break lines and stream intersections

2) Output not validated against contours, but should be better than main stem results at intersections

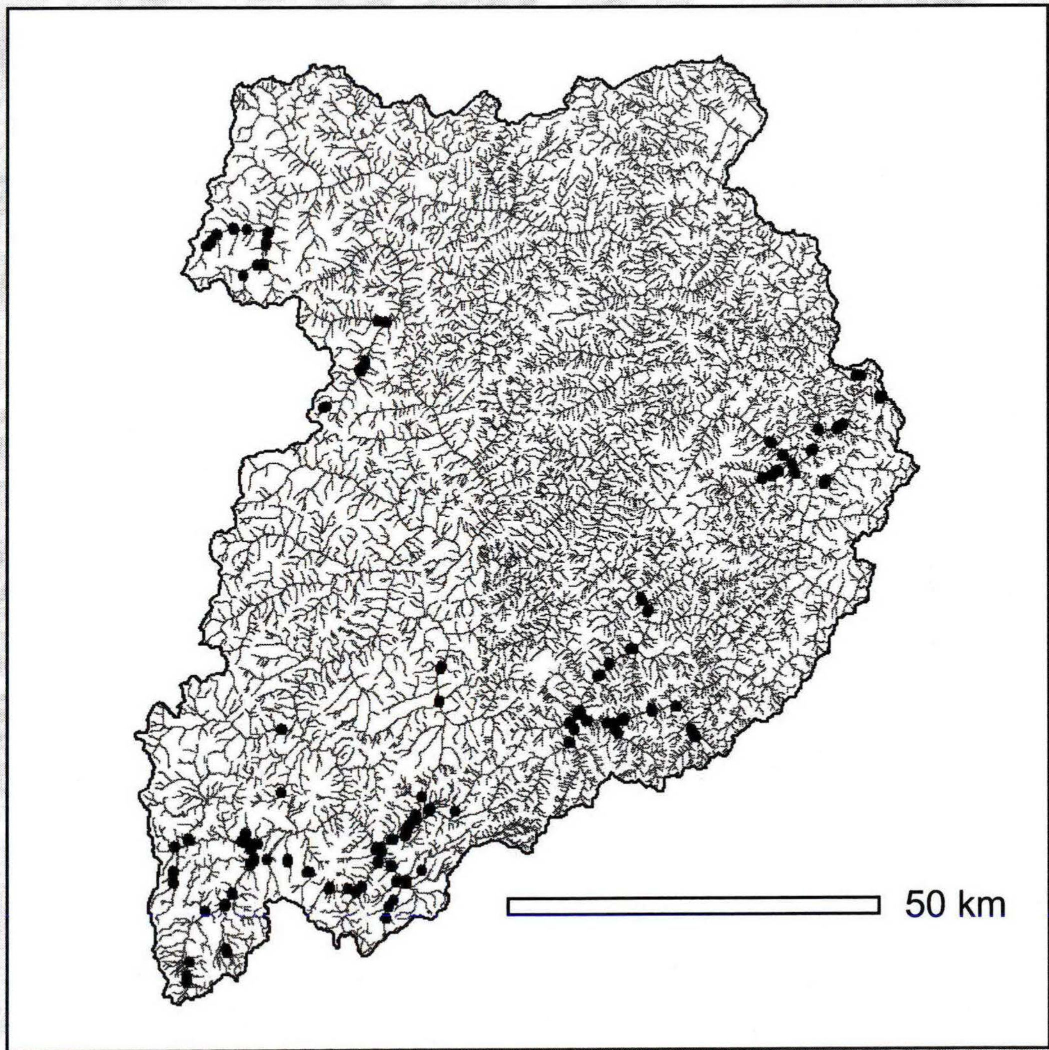
Average error < .39% pts

Final Stream Gradient Map

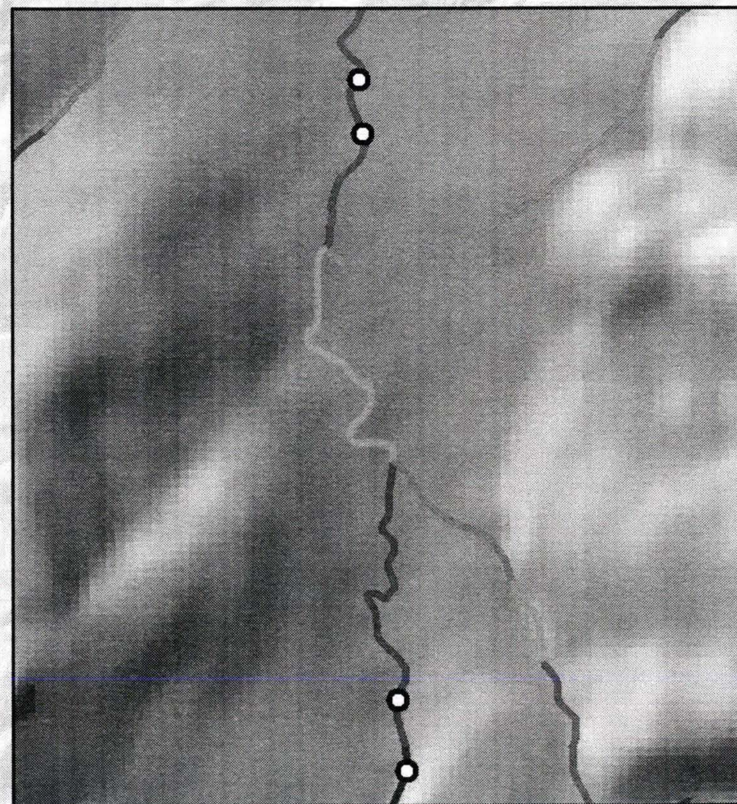


Field Data

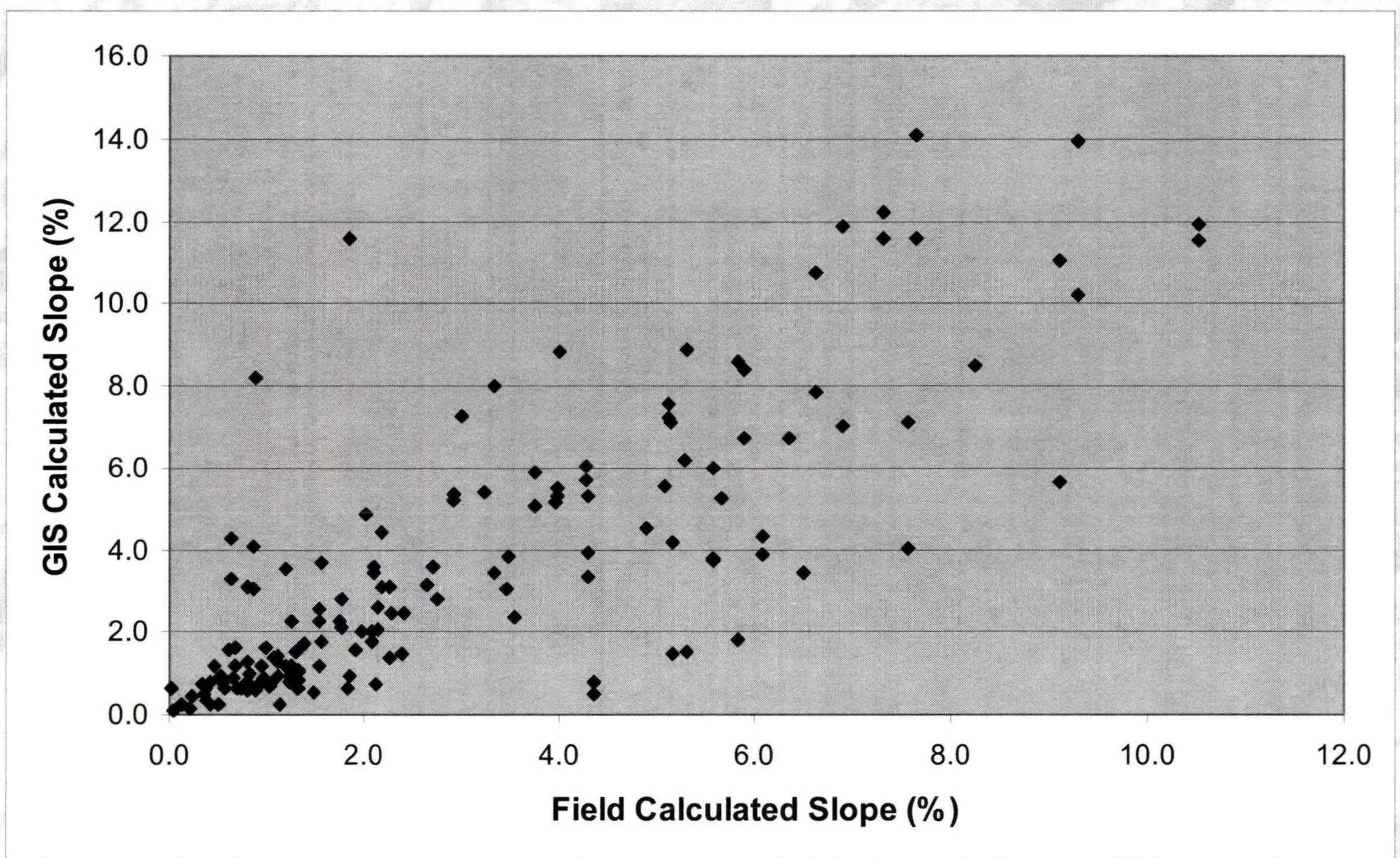
Field Calculated vs. GIS Calculated Gradient



n = 238



Field Calculated vs. GIS Calculated Gradient



Average error = 1.54% pts

R-squared = .67

Conclusions

1) The most appropriate interval spacing for measuring slope in higher gradient areas is about 100 m when using 10 m DEM data. Average error ~ 0.68% pts.

2) For main stem, low gradient channels, gradient is best computed between quad contour intervals. Average error ~ 0.03% pts.

3) At intermediate slopes, gradient can be computed between valley bottom break lines and stream intersections with 10 m DEM data. Average error < 0.39% pts.

Recommendation

10 m DEM data have variable accuracy dependent on slope and landscape position

Fish and watershed models that incorporate stream gradient should account for these errors

Acknowledgements

RMRS – Boise Lab

John Buffington – Research Geomorphologist
Dan Isaak – Research Fisheries Biologist

Bruce Rieman – Research Fisheries Biologist
Russ Thurow – Research Fisheries Biologist

Sharon Parkes – GIS Specialist
Dona Horan – Fisheries Biologist

Jim McKean – Research Geomorphologist
Carolyn Bohn – Hydrologist

Bob Smith – Idaho Department of Lands

8 APPENDIX C: PERFORMANCE OF THE SEDIMENT ROUTING MODEL,
Draft manuscript by Lewicki et al.